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Initial Assessment of Graphite Precipitates in Vermicular Cast Iron in the As-Cast State and after Thermal Treatments

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Abstract

The purpose of the work was to determine the morphology of graphite that occurs in vermicular cast iron, both in the as-cast state and after heat treatment including austenitization (held at a temperature of 890 °C or 960 °C for 90 or 150 min) and isothermal quenching (i.e. austempering, at a temperature of 290 °C or 390 °C for 90 or 150 min). In this case, the aim here was to investigate whether the heat treatment performed, in addition to the undisputed influence of the cast iron matrix on the formation of austenite and ferrite, also affects the morphology of the vermicular graphite precipitates and to what extent. The investigations were carried out for the specimens cut from test coupons cast in the shape of an inverted U letter (type IIb according to the applicable standard); they were taken from the 25mm thick walls of their test parts. The morphology of graphite precipitates in cast iron was investigated using a Metaplan 2 metallographic microscope and a Quantimet 570 Color image analyzer. The shape factor F was calculated as the quotient of the area of given graphite precipitation and the square of its perimeter. The degree of vermicularization of graphite was determined as the ratio of the sum of the graphite surface and precipitates with F <0.05 to the total area occupied by all the precipitations of the graphite surface.
The examinations performed revealed that all the heat-treated samples made of vermicular graphite exhibited the lower degree of vermicularization of the graphite compared to the corresponding samples in the as-cast state (the structure contains a greater fraction of the nodular or nearly nodular precipitates). Heat treatment also caused a reduction in the average size of graphite precipitates, which was about 225μm^2 for the as-cast state, and dropped to approximately 170-200 μm^2 after the austenitization and austempering processes.

Keywords: Vermicular cast iron, Graphite precipitates, Austempering

1. Introduction

Cast iron with vermicular precipitates of graphite, both in terms of mechanical properties – essential for the practical use of this alloy – and thermal conductivity, is situated between cast iron with spheroidal graphite and cast iron with flake graphite. This conductivity is close to that of grey cast iron with a pearlitic matrix [1]. This is related to the shape of the graphite particles, which take the intermediate shape between the graphite particles in both compared types of cast iron. The properties of the alloy are significantly influenced by the fact that the "worm-like" precipitates of graphite occurring in vermicular cast iron do not merge with each other and do not form a kind of graphite skeleton, which is characteristic of cast iron with flake graphite.

For many years, after the invention of spheroidal graphite cast the iron, in the 1950s and even 1960s, vermicular cast iron was regarded as an "unsuccessful" ductile iron. However, for some decades, the use of cast iron with vermicular graphite has been increasing [2-6]. Although the production of vermicular cast iron castings is considered very difficult, due to the requirement to keep the amount of spheroidizer in the alloy within strictly defined narrow limits [7], this type of cast iron is used to make, among other things:

- castings of combustion engine blocks with a high degree of compression and a high combustion temperature of the mixture, engine heads, ingot moulds, piston rings, brake discs, exhaust manifolds [1];
- gears, parts of machine tools subjected to vibrations during operation, bodies of turbochargers [8];
- moulds for the glass industry [9].

A characteristic feature of the structure of vermicular cast iron in the cast form is usually about 50% of ferrite. This is related to a higher number of graphite precipitates and shorter distances between them than in ductile iron, which facilitates the diffusion of carbon during the eutectoid transformation of austenite and the ferritization of the matrix [10]. There are three types of vermicular graphite [10]:

- with a maximum length of 20µm, the ratio of length to thickness 2÷4;
- with a maximum length of 150µm, the ratio of length to thickness 3÷5;
- with a maximum length of 150µm, the ratio of length to thickness 3÷10;

Vermicular cast iron is one of the materials that have not been the subject of multiple studies. This also applies to detailed metallurgical research. For example, it can be stated that the works published in the last dozen years [11-16] dealt with austempered vermicular cast iron, but in none of these works, the precipitates of vermicular graphite were the subject of detailed studies.

Therefore, it seems advisable to assess the graphite particles present in vermicular cast iron, considering their features. It is also important to determine the impact of heat treatment, namely austenitizing annealing and isothermal hardening, on the precipitation of graphite. It should be noted that different thermal treatments of cast iron significantly affect the resulting microstructure of the alloy and thus its mechanical properties. For example, it can be stated that quenching at a temperature of 370 °C and above leads to the appearance of relatively thick precipitates of ferrite in the matrix; at lower temperatures, the components of the dispersion of the matrix structure components and strength increase, and the plasticity of cast iron decreases [17]. Furthermore, the austenitizing temperature affects the mechanical properties as it increases and the proportion of high carbon austenite increases, which may result in the degradation of plasticity.

2. Results and Discussion

The investigation aimed to determine the morphology of graphite precipitates that occur in vermicular cast iron, both as cast and after heat treatment, including austenitizing annealing and isothermal hardening. It was about determining whether and to what extent the thermal treatments mentioned affect the precipitation of graphite.

Cast iron was produced in one of the domestic iron foundries. The base cast iron was melted in an acid-lined medium frequency induction furnace, and then the material was vermicularized, including "conditioning" of the alloy [11]. Table 1 shows the chemical composition of the investigated cast iron, determined using a spectrometer, in case of carbon and sulfur content in the alloy, additionally, the results of the analysis performed with the LECO analyzer were considered.

The reason for such a course of proceedings was the inability to precisely determine the content of both elements by means of spectral analysis. The data in Table 1 show that there are clear differences in the determination of the carbon and sulfur content in cast iron. According to spectral analysis, the carbon content in the alloy is "underestimated" (by approximately 0.25%) and the sulfur content is "overestimated" (by approximately 0.07%). It should be noted that knowing the actual sulfur content of the cast iron is extremely important in the technology of vermicular cast iron [18,19]. The addition of copper to cast iron (in an amount of approximately 1%) aimed at partial perlitization of the cast iron matrix at least and thus counteracting the natural tendency of vermicular cast iron to ferritize the matrix. The isothermal quenching of the alloy is then facilitated [1], which leads to a marked increase in the mechanical properties of the material [20-23].

Table 1.
Chemical composition of the investigated cast iron

Content [%]								
C*	C	Si	Mn	Cu	P	S*	S	Mg
3.52	3.27	2.80	0.20	0.98	0.051	0.013	0.020	0.017
*- the content determined with a LECO analyser								

From the cast iron produced, the test tubes consisted of cast in the shape of an inverted U letter (type IIb) according to the standard [24]. From the walls of the 25mm thick test part, samples were cut out for both metallographic tests of the alloy as cast and for determining the basic mechanical properties. The structure of cast iron after heat treatment was evaluated in samples cut from the grip parts of the strength tests.

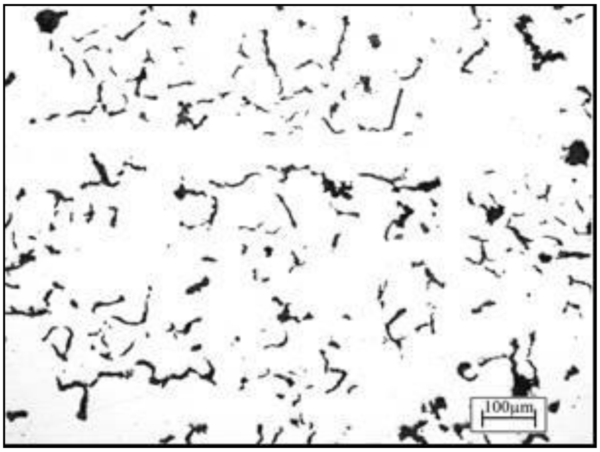
Figure 1 shows the shape and size of graphite precipitates in vermicular cast iron, as well as its microstructure. The sample for metallurgical tests came from a test ingot poured in the first minute of pouring the moulds.

The morphology of graphite precipitates in cast iron was investigated using a Metaplan 2 metallographic microscope and a Quantimet 570 colour image analyser. They included the determination of the number of graphite particles, areas occupied by these particles, their circumferences and lengths, and the share of graphite particles in the total surface area occupied by them, considering the classes of their shape coefficient. The graphite precipitate measurements were carried out at a magnification of 250x, and the analysis covered 25 fields in each test sample.

Shape factor F was determined for each separate graphite separation, according to the formula [24]:

$$F = \frac{P}{C^2} \qquad (1)$$

where:
P- graphite precipitation surface, mm^2;
C- graphite precipitation circuit, mm.
The shape index values determined as follows are as follows: for a circle, 0.08; for the square of 0.0625; for an equilateral triangle, 0.047.

a)


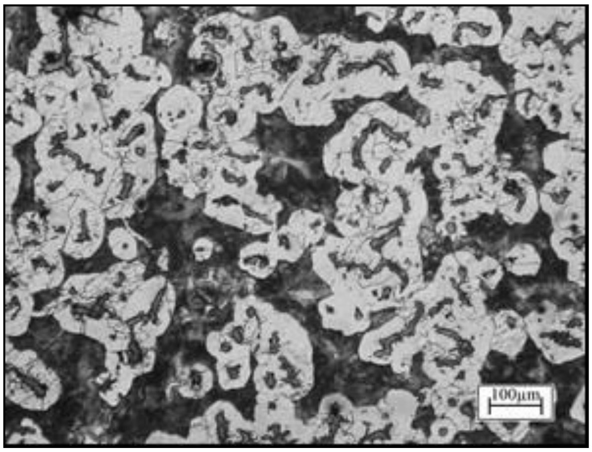
b)


Fig. 1. Cast iron with vermicular graphite as poured; a) shape and size of graphite particles, nonetched specimen; b) microstructure of cast iron, metallographic specimen etched with Nital

Table 2 presents more detailed data on the different thermal treatments of vermicular cast iron, as well as the average sizes of the surfaces, circumferences, and the number of graphite precipitates for the samples considered in the cast form and after treatment. The table also shows the average size of the graphite particles that occur in cast iron and the degree of vermicularization of the graphite. The value of the latter parameter was determined according to the formula:

$$\eta_w = \frac{\sum P_{(F \le 0,05)}}{\sum P} \cdot 100\% \qquad (2)$$

where:
η_w – graphite vermicularization degree, %;
P – graphite precipitation surface, mm^2;
F – graphite precipitation shape factor.

The data in Table 2 show that all heat treated vermicular cast iron samples showed a decrease in graphite vermicularization compared to cast iron (see the data in column 10). This indicates an increase in the proportion of graphite particles with a shape close to spherical and a decrease in the area of graphite particles with a shape similar to vermicular.

As a result of heat treatment, the average size of graphite particles decreased significantly, and for all its parameters (see data in col. 9, Table 2). And, if in the case of cast iron, it was 225μm^2, after austenitization and isothermal hardening, it dropped to approx.170-200 μm^2. However, the results of metallographic studies did not allow for the capture of the unambiguous influence of the austenitization temperature and its duration (in the adopted intervals) on the changes in the size of the analyzed precipitates.

Figure 2 shows the share of areas occupied by graphite precipitation, characterized by the shape factor belonging to one of the eight adopted ranges.

Figure 3 shows the shares of the quantity of graphite particles, characterized by shape factors that belong to one of the adopted ranges.

The analysis of the data presented in Figure 2 allows one to assess the impact of thermal treatment on the share of the graphite area occupied by the precipitation of graphite with the shape factor in the adopted ranges of the value of this parameter. There is a particularly clear tendency to decrease - due to the heat treatment of cast iron - the surface covered by the precipitation of graphite with a shape factor in the range (0.0 0.01>. Although the share of the area occupied by this type of graphite precipitation in cast iron exceeded 25%, due to treatments, it decreased to the level of approximately 5% (test no. 110) to approximately 17% (test nos. 71 and 69).

The tendency of vermicular cast iron to increase the surface area occupied by graphite precipitates of almost spherical shape (characterized by the shape factor F> 0.05), due to thermal treatment, was accompanied by a significant trend toward a significant increase in the number of precipitates (compare the data in Figure 3). Although in the case of cast iron, they represented approximately 25% of the total number of graphite precipitates, after austenitization and hardening of the material, their share increased to the range of approximately 34% (test 71) to approximately 42% (test 119).

It is impossible to compare the obtained data with the available literature because no scientific reports concerning the influence of the discussed heat treatment on the morphology of the graphite particles have been encountered.

Table 2.
Different thermal treatments of vermicular cast iron and the average size of the surface occupied by the graphite particles, their circumferences and numbers, as well as the average graphite size of the graphite particles occurring in cast iron

No.	Test No.	Temperature and time of austenitization		Tempering temperature and time		The area occupied by the precipitation of graphite [%]	Graphite precipitation circuit [1/mm]	Graphite precipitation number [1/mm^2]	Average size of the graphite precipitates [μm^2]	Graphite vermicularization degree [%]
	1	2	3	4	5	6	7	8	9	10
1	64	cast form				10,87	42.87	483.64	225	94.04
2	73	960	150	390	90	8,75	35.99	502.66	174	90.49
3	110	960	90	390	90	10,49	36.73	561.54	187	86.09
4	71	960	120	340	120	9,88	39.42	566.63	174	92.63
5	119	925	150	340	120	10,21	37.02	578.32	176	87.73
6	69	925	90	340	120	9,67	36.36	485.58	199	92.05
7	101	925	120	340	120	9,82	37.25	581.92	169	88.92
8	82	925	120	290	120	8,60	37.46	582.22	148	88.89
9	91	890	150	390	150	8,79	38.92	595.70	148	89.47
10	75	890	90	390	150	9,28	37.53	533.52	174	91.81
11	74	890	120	340	120	10,17	36.64	524.08	194	90.12

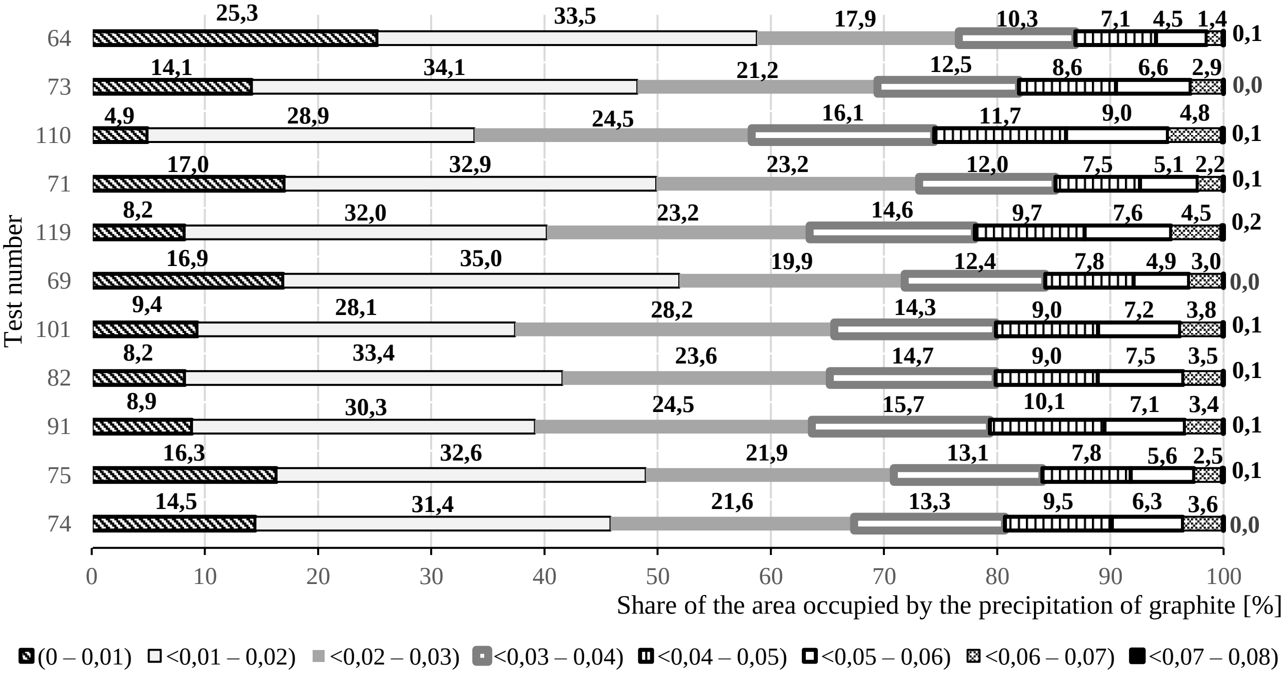


Fig. 2. The share of areas occupied by the precipitation of graphite with the shape factor in each range. Vermicular cast iron heat treatment parameters according to Table 2

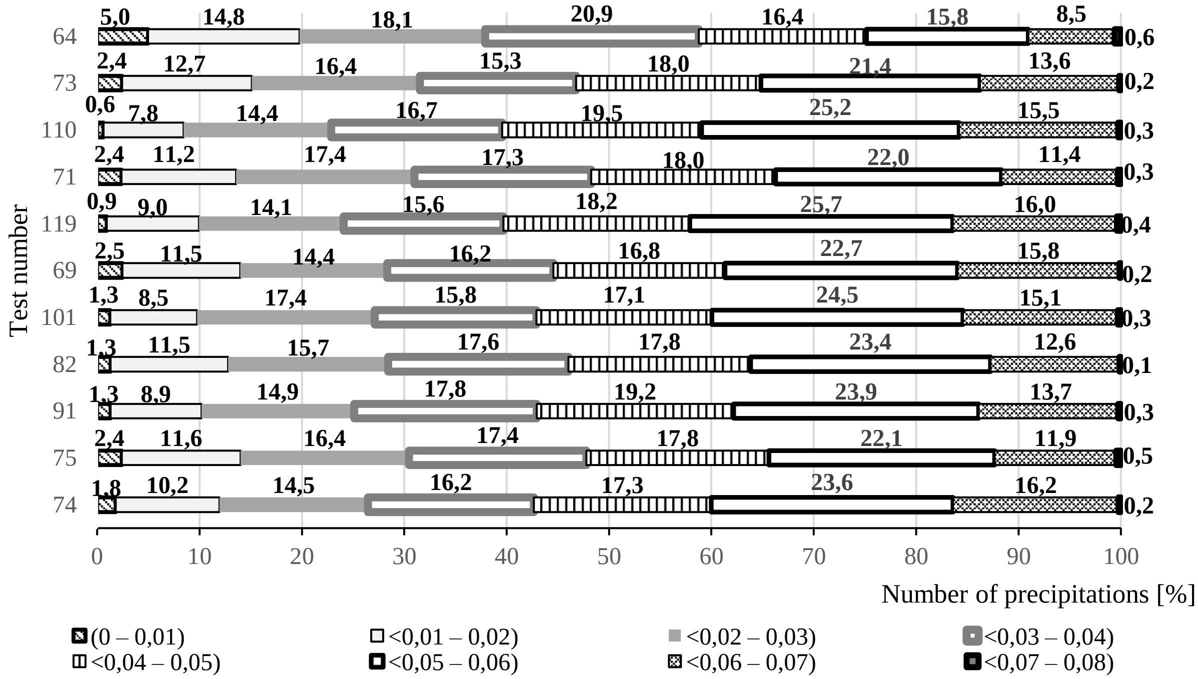


Fig. 3. Shares of graphite the number of graphite particles with the shape factor in each range. Vermicular cast iron heat treatment parameters of vermicular cast iron in accordance with Table 2

3. Summary

1. As a result of heat treatment, the average size of graphite particles decreased significantly. If, in the case of cast iron, it was 225µm^2, after austenitization and isothermal hardening, it dropped to approx.170-200 µm^2.
2. There is a particularly clear tendency to decrease - due to the heat treatment of cast iron - the surface covered by the precipitation of graphite with a shape factor in the range (0.0 0.01>.
3. The tendency of vermicular cast iron to increase the surface area occupied by the precipitates of graphite with an almost spherical shape, because of the thermal treatment, was accompanied by a significant predisposition to a significant increase in the number of precipitates. Although in the case of the cast iron as-cast state, they accounted for about 25% of the total number of graphite precipitates, after austenitization and hardening of the material, their share increased to the range from about 34% to about 42%.

Concluding the summary, it should be noted that changes in the morphology of graphite precipitates probably contribute to a significant impact on the increase in the mechanical properties of vermicular cast iron due to isothermal quenching [20-22], apart from the indisputable influence of changing the cast iron matrix.

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