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The Effect of Structure on Thermal Power of Cast-iron Heat Exchangers

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Abstract

The objective of the study reported in this paper was to determine the effect of structure on thermal power of cast-iron heat exchangers which in this case were furnace chambers constituting the main component of household fireplace-based heating systems and known commonly as fireplace inserts. For the purpose of relevant tests, plate-shaped castings were prepared of gray iron with flake graphite in pearlitic matrix (the material used to date typically for fireplace inserts) as well as similar castings of gray cast iron with vermicular graphite in pearlitic, ferritic-pearlitic, and ferritic matrix. For all the cast iron variants of different structures (graphite precipitate shapes and matrix type), calorimetric measurements were carried out consisting in determining the heat power which is quantity representing the rate of heat transfer to the ambient environment. It has been found that the value of the observed heat power was affected by both the shape of graphite precipitates and the type of alloy matrix. Higher thermal power values characterize plate castings of gray iron with vermicular graphite compared to plates cast of the flake graphite gray iron. In case of plates made of gray cast iron with vermicular graphite, the highest values of thermal power were observed for castings made of iron with ferritic matrix.

Keywords: Heat exchanger, Gray cast iron, Thermal power

1. Introduction

The main component of any household wood-fired fireplace is the furnace chamber known commonly as the fireplace insert. The structure belongs to a wide class of devices used in different heat-generating systems called the heat exchangers.

The choices made as far as a specific type of fireplace insert is concerned, depend on the fireplace operating schedule (occasional or continuous usage), the surface area of the living space to be heated, technical parameters and service properties of the material used, and, last not but least, aesthetic qualities.

Cast-iron fireplace inserts are manufactured in two basic variants. They are offered as cast iron elements put together with the use of bolted joints or as single-piece cast monolithic bodies.

The basic material used to fabricate fireplace inserts is the gray cast iron. Microstructure of the matrix of gray irons depends on chemical composition of the alloy and conditions of its solidification (the cooling rate). The castings for fireplace inserts are characterized with walls of relatively small thickness. This means conditions favorable to higher cooling rates, pearlitic structure of matrix, and fineness of graphite precipitations.

According to [1], the increase of carbon content in the flake graphite gray iron from 2.8% C to 3.6% C, at almost invariable content of silicon (about 1.8% Si) and manganese (about 0.5% Mn), is accompanied by the increase of thermal conductivity of the material by 15–17 W/(m K).

With increasing temperature of the flake graphite cast iron, a decrease of the thermal conductivity value can be observed, which is the stronger, the higher is the carbon content. For instance, in a cast iron with flake graphite containing 4.75%

C, the increase of the material temperature from 100°C to 400°C resulted in reduction of the thermal conductivity value by 30 W/(m K), but in case of cast iron containing 3.25% C, the observed conductivity decrease was only 8 W/(m K) [2].

Authors of [1] report that in case of flake graphite cast iron of grades ranging from GJL-150 to GJL-400, the increase of temperature of the material from 100°C to 400°C resulted in reduction of the thermal conductivity value only by 3 W/(m K). However, a certain level of caution should be exercised with respect to thermal conductivity values claimed in the literature as, for instance, the paper [3] quotes after [4] that with the cast iron grade increasing from GJL-150 to GJL-350, the thermal conductivity value decreased by 17 W/(m K).

Thermal conductivity of gray cast iron decreases with increasing content of silicone [2, 5]. According to [3], at temperature 100°C, value of the thermal conductivity varies within the range of 71–80 W/(m K) for ferrite and 50–53 W/(m K) for pearlite, whereas at temperature 500°C, the values decrease by 28–38 W/(m K) and 6–9 W/(m K), respectively.

Recent years show an increased interest in gray cast iron with vermicular graphite. Compared to the flake graphite gray iron, the material demonstrates higher mechanical strength properties, better plastic behavior, and lower sensitivity to thickness of casting walls. For this reason, the cast iron of this very type is more and more commonly used for castings operated under conditions involving exposure to combustion gases and cyclically variable thermal loads, such as cast exhaust manifolds for motor-car engines [6, 7]. In castings of the flake graphite gray iron, definitely premature cracks appeared at operating temperatures just above 500°C, whereas castings of gray iron with nodular graphite turned out to be excessively prone to getting warp which resulted in damaged gaskets and ruptured bolts [6].

A characteristic feature of cast irons with vermicular graphite, when compared to flake graphite cast iron, is the opposite sign of the thermal conductivity value change with increasing temperature. In case of the vermicular graphite cast iron, the thermal conductivity coefficient increases with rising temperature [8–10].

According to authors of [9], the thermal conductivity coefficient value for gray iron with vermicular graphite is comparable with the corresponding value for the flake graphite gray iron. With increasing content of nodular graphite, value of the thermal conductivity coefficient characterizing the cast iron with vermicular graphite decreases.

The above-quote literature figures reveal certain discrepancies between the thermal conductivity coefficient values reported for gray cast irons with flake graphite on one hand and vermicular graphite gray irons on the other.

The objective of the study was to asses the effect of the form of graphite precipitations and type of the matrix on thermal power characterizing cast-iron heat exchangers which is directly related to the flux of heat transmitted to environment by these components of heat-generating systems.

2. Test material and methodology

The material subject to testing were plate-shaped castings with dimensions 280 mm × 240 mm × 5 mm, made of gray cast iron with flake graphite in pearlitic matrix (the material used nowadays most commonly for fireplace inserts) and similar plate castings of gray iron with vermicular graphite in ferritic, ferritic-pearlitic, and pearlitic matrix. All the test specimens were cast in sand molds.

In case of plates cast of the vermicular graphite iron, the process of vermiculation was carried out with the use of the CEDIFIL NCF 4800 wire. The used quantity of the wire resulted in the magnesium content in the cast iron maintained within the range of 0.018–0.022% Mg.

Chemical composition of the tested flake graphite and vermicular graphite gray irons is listed in the following table.

Table 1.
Chemical composition of plates used for testing the heat emission to environment (element contents, % by weight)

Gray cast iron with flake graphite						
C	**Si**	**Mn**	**P**	**S**	**Mg**	**Fe**
3.71	2.15	0.87	0.05	0.02	0.003	t.b.
Gray cast iron with vermicular graphite						
C	**Si**	**Mn**	**P**	**S**	**Mg**	**Fe**
3.65	2.05	0.47	0.03	0.03	0.020	t.b.

The thermal treatment applied to obtain the gray cast iron with vermicular graphite in ferritic matrix, consisted in heating the castings up to temperature 920°C, keeping them at the same temperature for 2 hours, and cooling them at the rate of 200°C/hour.

To obtain the pearlitic matrix, the applied heat treatment involved heating the cast-iron plates up to 920°C, maintaining them at the temperature for 2 hours, and cooling in ambient air.

Microstructure of the cast plates was examined with the use of VEGA scanning electron microscope (TESCAN).

Calorimetric measurements were taken on a setup for evaluation of heat emission to ambient environment shown schematically in Figure 1.

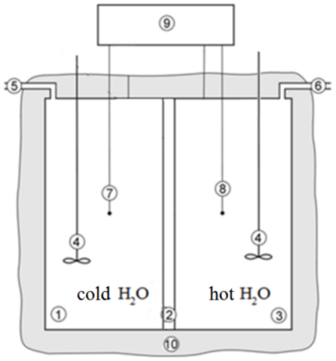

Fig. 1. Schematic diagram of the set-up used for heat emission tests; 1 — cold water tank; 2 — tested gray iron plate; 3 — hot water tank; 4 — temperature-equalizing agitators; 5 — cold water inlet; 6 — hot water inlet; 7 — thermocouple to measure cold water temperature; 8 — thermocouple to measure cold water temperature; 9 — temperature meter; 10 — thermal insulation of the tanks

The set-up for testing the heat emission rate was designed and built in the Rzeszów University of Technology's Department of Foundry and Welding as a result of analysis of solutions developed for the purpose of calorimetric measurements of welding processes [11–13].

The heat-carrying medium used in the test was water pre-heated to temperature of (85 ± 2)°C. The test started at the moment of filling the hot tank with water pre-heated up to temperature of (85 ± 2)°C, while the cold water contained in the cold tank had temperature of (10 ± 2)°C. To ensure homogeneity of temperature distribution in both water tanks, low-speed agitators were used which allowed to neglect the additional energy introduced by them to the overall heat balance.

To measure temperature of water in each of the two tanks, two thermocouples were used connected to HD 9016 multi-channel digital thermometer. The basic parameter measured in the test was the time period after which temperature of water in the cold tank reached the value of 40°C.

The quantity of heat energy transferred to the cold water tank could be then determined from the formula

$$\Delta Q = m_w \, c_w \, \Delta T, \tag{1}$$

where ΔQ is the quantity of heat introduced to the cold water tank, J; m_w — mass of water in the cold water tank, kg; c_w — specific heat of water, J/(kg K); and ΔT — cold water temperature increase, °C (K).

The heat flow rate, or in other words, the thermal power characterizing the energy exchange process, was evaluated with the use of formula

$$\Phi = \Delta Q / \Delta t, \tag{2}$$

where Φ is the average heat flow rate characterizing energy transfer from hot water to cold water tank; kJ/s (kW), ΔQ — the quantity of heat transferred to the cold water tank, kJ; and Δt — the test duration time, s.

3. Research results and analysis

Images of microstructure observed in castings of gray irons with flake graphite and with vermicular graphite in different types of matrices are presented in Figures 2 and 3.

Results of thermal power value measurements carried out for plate castings with different microstructure are listed in Table 2.

Table 2.
Thermal power values measured for plate castings of gray irons with different microstructure

Gray iron plate casting microstructure	**Thermal power, kW**	
	range	**average value**
Flake graphite, pearlite	0,511-0,519	0,515
Vermicular graphite, pearlite	0,584-0,600	0,592
Vermicular graphite, pearlite, ferrite	0,672-0,690	0,681
Vermicular graphite, ferrite	0,694-0,708	0,701

The obtained results indicate that in case of the cast iron with pearlitic matrix, the switching of the graphite precipitation morphology from flake-shaped to vermicular resulted in the increase of the heat quantity emitted to the ambient environment in the course of the test by about 15% which, when translated into operating effectiveness of a cast-iron fireplace insert, means that the gray iron with graphite precipitates in vermicular form is the most favorable option among the tested materials.

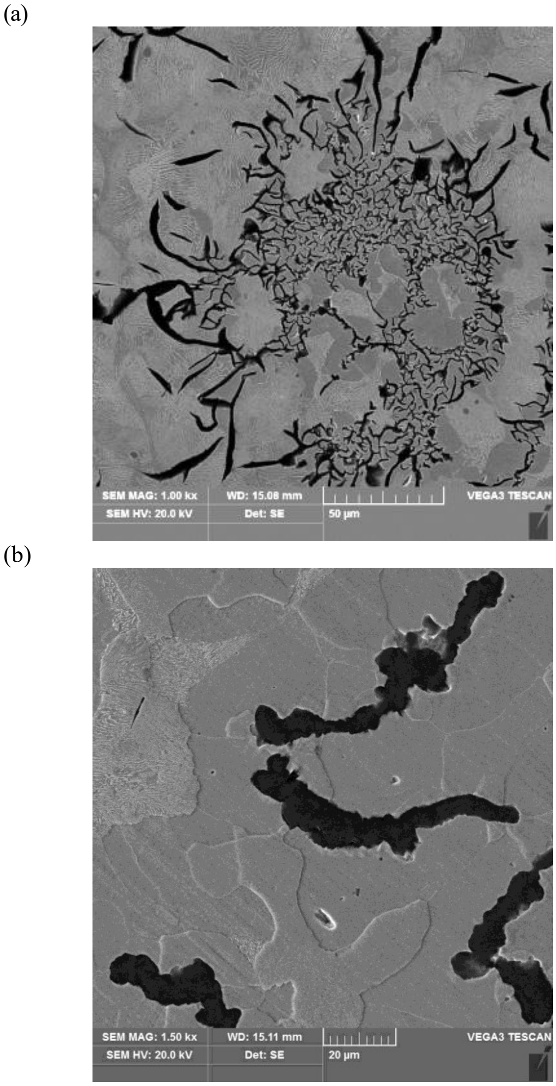

Fig. 2. Microstructure observed in test plate castings: (a) flake graphite, pearlite, trace ferrite; (b) vermicular graphite, ferrite, pearlite. Etched in 4% HNO_3

It has been also found that the type of matrix observed in vermicular cast iron has an effect on intensity at which the material gives up the heat to the environment. The lowest thermal power value was observed for plate-shaped castings of gray iron with flake graphite in pearlitic matrix, while the highest value, exceeding the latter by about 20%, was measured for test plates cast of gray iron with vermicular graphite in ferritic matrix. Other variants of the material, with microstructure showing vermicular graphite precipitates in ferritic-pearlitic matrix, demonstrated intermediate values of the thermal power.

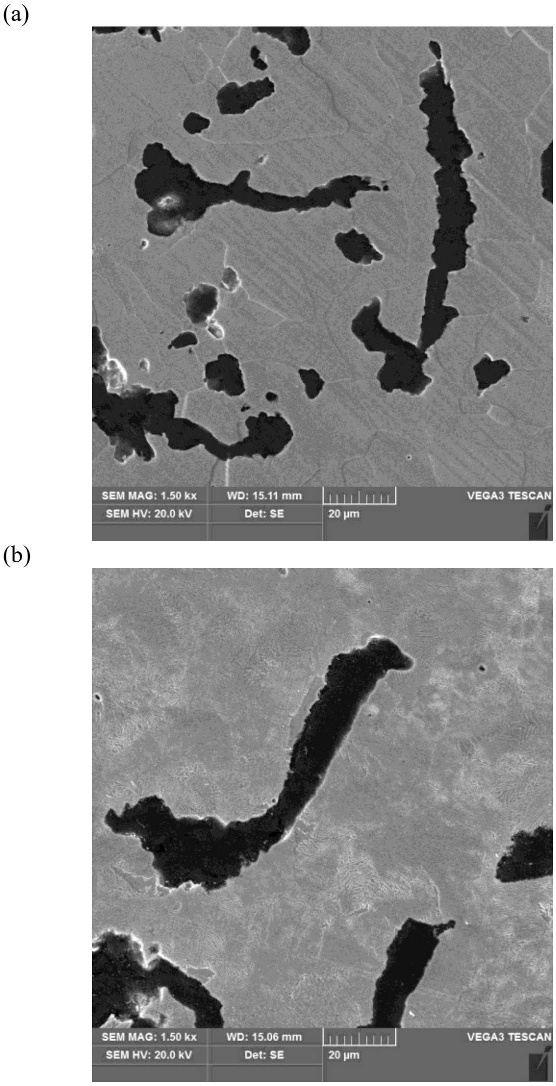

Fig. 3. Microstructures observed in test plate castings: (a) vermicular graphite, ferrite; (b) vermicular graphite, pearlite. Etched in 4% HNO_3

4. Conclusions

Results of the above-described tests can be summarized as follows:

- The effectiveness at which a fireplace insert cast of gray iron depends on both the shape (flake, vermicular) of graphite precipitates observed in the material and the type of matrix (pearlitic, ferritic-pearlitic, ferritic). The highest values of thermal power were obtained when gray iron with vermicular graphite in ferritic matrix was used for plate-shaped model heat exchangers.
- By using gray cast irons with vermicular graphite to manufacture fireplace inserts instead of flake graphite gray irons preferred to date, it will be possible to improve thermal efficiency of the fireplace-based heating systems.

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