ARCHIVES
of
FOUNDRY ENGINEERING

10.24425/afe.2021.138685

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 2021
Issue 4/2021

93 – 96

13/4

Influence of Microstructure and Heat Transfer Surface on the Thermal Power of Cast Iron Heat Exchangers

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Received 30.09.2021; accepted in revised form 23.11.2021

Abstract

The paper presents the results of calorimetric tests of segment elements of fireplace inserts. The aim of the work was to optimize their thermal power by replacing the previously used gray cast iron with flake graphite with gray iron with vermicular graphite and replacing the existing geometry of the heat transfer surface with a more developed one. It turned out that the thermal power of the test segments made of cast iron with vermicular graphite was higher compared to the segments of the same shape made of gray cast iron with flake graphite. It was found that the use of segments made of vermicular cast iron with a ferritic matrix allowed for an increase in the thermal power value by dozen percent, compared to segments of the same shape made of vermicular cast iron with a pearlitic matrix. The test results showed that the thermal power of the test segments depends on the variant of the development of both the heat receiving surface and the heat giving off surface. The highest value of the thermal power was obtained when ribbing in the form of a lattice was used on both of these surfaces, and the lowest when using flat surfaces.

Keywords: Vermicular cast iron, Heat exchanger, Thermal power, Calorimetric test

1. Introduction

The world's growing energy production is accompanied by ever higher greenhouse gas emissions, resulting in climate changes occurring on all continents. As it turns out, most pollutants are emitted into the environment by low-power energy sources. These include heating installations for individual households. Hence, the activities of the European Parliament [1, 2] are aimed at persuading producers to develop and produce boilers, stoves and fireplace inserts with a higher than now thermal efficiency of converting fuel energy into useful energy [3].

The authors of the study [4] state that in the case of a typical segmented fireplace insert type W8-19.7 kW with the use of hornbeam wood charge equal to 8 kg, with a fireplace draft of 12±2Pa, the maximum temperature of the side wall was 82°C, the rear wall was 74°C, and the basis was 31°C. The average temperature of the exhaust gases was 300°C. The thermal efficiency of the insert was estimated at 60%.

Unpublished studies of the microstructure and chemical composition of fireplace inserts produced in Denmark, France, Croatia or Poland have shown that they are made of gray cast iron with a pearlitic matrix with precipitates of flake graphite. This cast iron was characterized by the following range of variability of the alloying elements 2.60-3.13% C, 1.90-2.26% Si, 0.45-0.80% Mn, 0.03-0.07% P, 0.03-0.17% S, the rest iron. In the works on the development of a new generation of fireplace inserts, characterized by a better use of the heat of combustion of the fuel, it is necessary to develop a microstructure of cast iron characterized by a high value of the heat conductivity coefficient and to apply such variants of the heat receiving surface and the heat giving off the surface that will increase the amount of heat transferred to the environment. This requires acquiring new knowledge in this area.

According to the authors of the papers [5, 6], in the case of gray cast iron with flake graphite, the thermal conductivity increases with increasing carbon content. It is also known that increasing the carbon content in gray cast iron with flake graphite from 3.75 to 4.75% increased the value of the thermal conductivity coefficient from 48 to 80W/(mK) [5]. These results concerned measurements at a temperature of 100°C. The thermal conductivity of gray cast iron decreases with an increase in the silicon content, although on the other hand, the increase in the silicon content is accompanied by an increase in the volume fraction of ferrite [5, 7], which thermal conductivity coefficient value at a temperature of 100°C is 11-80W/(mK) according to [5]), while in the case of pearlite it is 50-53W/(mK). Due to the force with which the alloying elements reduce the value of the thermal conductivity coefficient, they were ranked in the following order: Si, Al, M, Ni, Co.

It is also suggested [8] that the microstructure of the cast iron matrix (cast iron class) has an influence on the value of the thermal conductivity coefficient. The value of the thermal conductivity of the GJL-150 cast iron was 59W/(mK), and the GJL-350 cast iron was less than 42W/(mK) [9]. It is known that GJL-350 grade cast iron contains more pearlite in the matrix.

According to the authors of the paper [10], the value of the thermal conductivity coefficient of gray iron with vermicular graphite is comparable to its value for gray iron with flake graphite. The problem of the influence of the microstructure on the value of the thermal conductivity coefficient of cast iron is more complex, because the method of shaping the matrix microstructure is also important, whether it is in the raw state or after heat treatment. During austenitization, the precipitates of graphite dissolve and gaps are formed at the graphite-matrix interface. The density of cast iron also decreases [11]. Due to the fact that heat propagation is a process of propagation of electromagnetic waves of appropriate length, which are reflected on the gaps between the matrix and graphite, the time of their passage through such material is extended. This results in a reduction in the value of the thermal conductivity coefficient. Therefore, cast iron with a pearlitic or ferritic matrix in the raw state will have a higher value of thermal conductivity than cast iron with such a matrix, but obtained by heat treatment. The result of using such cast iron for fireplace inserts will be their lower thermal power. As it turns out, the problem of decreasing the value of the thermal conductivity coefficient of the fireplace inserts material during their proper operation should not occur, because the measurement results of the wall temperature of the inserts [4] did not show values at which the pearlite decomposition process and diffusive carbon displacement processes could occur.

It should be assumed, however, that as a result of oxidation of the surface of the inserts, their thermal power may decrease. As demonstrated by the authors of the paper [12], the thermal power of fireplace inserts can be increased by applying coatings with a higher value of the thermal conductivity coefficient on the surface that gives off heat to the environment.

The presented state of knowledge indicates that the issue of improving the thermal power of cast iron fireplace inserts is complex and requires research.

The subject of this study was to demonstrate the possibility of improving the thermal power of segments of cast iron fireplace inserts in the cast state by using a different than before cast iron and a different shape of the heat exchange surface.

2. The material and methodology

The material for the research was cast iron plates with dimensions of 280 mm x 240 mm x 5 mm in the following variants: heat-receiving surface flat or with lattice-shaped ribs (Fig. 1), heat giving off the surface with straight ribs or with lattice-shaped ribs (Fig. 2).

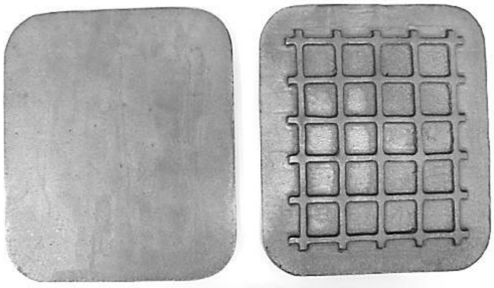

Fig. 1. An exemplary view of the heat receiving surface

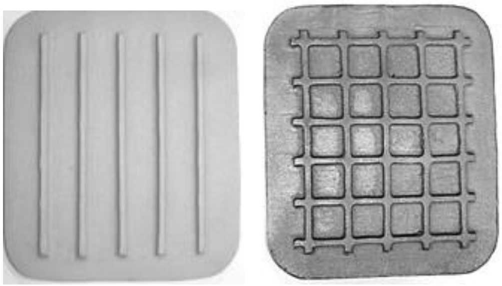

Fig. 2. An exemplary view of the heat giving off the surface

Casting sets with various surface shapes were made of gray cast iron with flake graphite with a pearlitic matrix, vermicular cast iron with a pearlitic matrix and vermicular cast iron with a ferritic matrix. The initial material for making castings, prepared under production conditions, was characterized by a low content of manganese, silicon and sulfur (4.08% C, 0.20% Mn, 2.05% Si, 0.01% S, 0.08% P). The castings were made in laboratory conditions with the use of a mains frequency induction furnace, with a capacity of 20kg of charge. At each melt, the furnace was filled with a metal charge weighing 16kg, which allowed for the production of two pieces of experimental castings. An example of an experimental casting is shown in Figure 3.

The melting process was carried out under the cover of the Schlackenbinder Gross slag coagulator. Additional metallurgical operations, such as modification in the case of gray cast iron with flake graphite, were performed using the FeSiBa modifier under the trade name MB-10 in the amount of 0.15% of the charge weight. A part of the modifier was placed in a pouring crucible heated to the temperature of 900°C, and a part was fed to a stream of liquid metal. The graphite vermicularization treatment was performed with the use of FeSiMg5 pre-alloy under the trade name Elmag®5800 in the amount of 0.6% of the charge mass, and the modification treatment with a portion of FeSiBa modifier in the amount of 0.15% of the charge mass. Both the pre-alloy and the modifier were placed on the bottom of the pouring crucible heated to the temperature of 900°C.

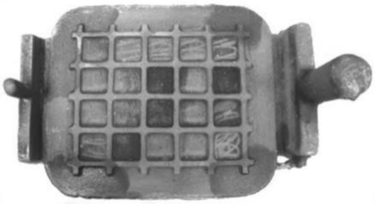

Fig. 3. View of an exemplary experimental casting after removing from the sand casting mold

The overheating temperature of the liquid alloy in the production of gray cast iron with flake graphite was 1300°C, and 1490°C in the case of the production of vermicular cast iron. The pouring temperature of plate castings to sand molds was 1265°C and 1280°C respectively. An example of the microstructure of test plate castings is shown in Figures 4-6.

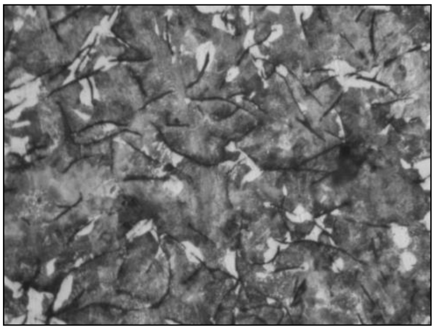

Fig. 4. Microstructure of test plate castings of gray iron with flake graphite; pearlite, traces of ferrite, flake graphite; digestion with 4% HNO3; magnification 300x

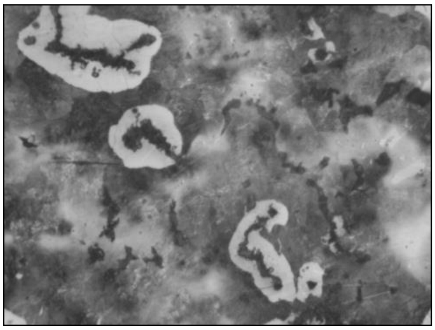

Fig. 5. Microstructure of test plate castings of vermicular cast iron; pearlite, traces of ferrite, vermicular graphite; digestion with 4% HNO3; magnification 300x

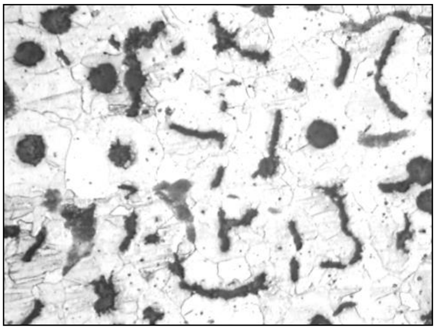

Fig. 6. Microstructure of test plate castings of vermicular cast iron; ferrite, vermicular graphite, spherical graphite; digestion with 4% HNO3; magnification 300x

The plate castings surfaces were cleaned by shot blasting.

Calorimetric tests of plates castings with different microstructure and different heat receiving and heat giving off surfaces were performed on the experimental stand described in paper [12]. The heat carrier used in the experiment was water with temperature of 85±2°C. The hot water chamber was closed on one side with test plate, with a heat receiving surface. To the second surface, giving off the heat, a cold water chamber with an initial temperature of 10±2°C was adjacent. The uniformity of the temperature distribution in the chambers during the measurements was ensured by mixing the water. The measurements did not take into account the energy introduced into the water in the mixing process, because low-speed mixers were used. Water temperature in both chambers was measured with the use of thermocouples connected to the HD 9016 multi-channel digital thermometer. During the test, the time t required to raise the temperature of the cold water to 40°C was measured.

The amount of heat Q introduced into the cold water chamber was determined from the formula:

$$Q = m_w \times c_w \times \Delta T \qquad (1)$$

where: m_w - the mass of water, c_w - the specific heat of water, ΔT - the increase of temperature of water.

The value of the heat flux (thermal power) φ was determined from the formula:

$$\varphi = \frac{Q}{t} \qquad (2)$$

where: φ - heat flux (thermal power), Q - amount of heat introduced into the cold water chamber, t – time.

3. Test results and analysis

The results of measurements and calculations of the heat flux (thermal power) are presented in Table 1.

The obtained results indicate that in the case of cast iron with similar chemical composition and a pearlitic matrix with traces of ferrite, the change in the shape of the flake graphite precipitates into vermicular ones increased the thermal power of the test castings of the plates. Even better results were obtained in the case of vermicular cast iron with a ferritic matrix.

Table 1
Heat flux (thermal power) of cast iron castings plates with different microstructures and different variants of the surface receiving and giving off heat

Variant of material	**Variants of the surface**		**Heat flux, kJ/s (Thermal power, kW)**
	heat receiving	**heat giving off**	
grey cast iron with flake graphite, pearlitic matrix	flat	with ribs	0.84
		with lattice	0.89
	with lattice	with ribs	0.91
		with lattice	0.98
vermicular cast iron, pearlitic matrix	flat	with ribs	0.95
		with lattice	0.99
	with lattice	with ribs	1.09
		with lattice	1.11
vermicular cast iron, ferritic matrix	flat	with ribs	1.10
		with lattice	1.14
	with lattice	with ribs	1.18
		with lattice	1.28

It turned out that a further increase in the thermal power of the test castings of the plates can be achieved by expanding their heat receiving and heat giving off surfaces.

4. Conclusions

Small combustion plants, which also include fireplaces, belong to the group that emits the most greenhouse gases into the environment, which results in progressive climate change. Hence, the improvement of the work efficiency (thermal power) of this type of heat exchangers is extremely important. It can be achieved by:

- the use of gray cast iron with a ferritic matrix with precipitates of vermicular graphite for the castings of fireplace inserts instead of used before the gray cast iron with a pearlitic matrix with precipitates of flake graphite,
- shaping the ribs in the form of lattice on the heat receiving and giving off the surface instead of the previously used flat heat receiving surface and straight ribs on the heat giving off surface.

Acknowledgements

The study presented in this paper was carried out as part of the project POIR.01.01.02-00-0113/16-00, Measure 1.1 “Enterprises’ R&D projects”, Sub-measure 1.1.2 “R&D works relating to fabrication of pilot/demonstrator plant”, implemented jointly by the Rzeszów University of Technology and KAW-MET Iron Foundry.

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