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Improvement of Operating Performance of a Cast-Iron Heat Exchanger by Application of a Copper Alloy Coating

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Abstract

The paper deals with possibility to improve operating performance of cast-iron heat exchangers by providing them with a copper alloy (CuTi2Cr) with the use of the flame spraying method. A test exchanger was cast of a gray cast iron with vermicular graphite in ferritic-pearlitic matrix obtained in production conditions at KAW-MET Iron Foundry with the wire method used to vermicularize the material. The test samples were two plates cast in sand molds, of which one was given a flame-sprayed CuTi2Cr coat on one side. The operating performance of such model cast-iron heat exchangers, with and without CuTi2Cr coating, was tested on a set-up for determining the heat flow rate (thermal power) transferred by the heat exchanger to environment. The obtained results indicate that the value of the heat flow rate characterizing the CuTi2Cr-coated cast-iron heat exchanger was by 10% higher compared to the flow rate of heat conveyed to environment by the heat exchanger without coating.

Keywords: Vermicular graphite cast iron, CuTi2Cr coating, Heat flow rate

1. Introduction

Heat exchangers are those device components which are responsible for heat exchange between different media. The multitude of available design solutions of heat exchangers is a result of wide range of applications, from boilers and heating systems to heat sinks for electronic devices.

Fireplace inserts constituting key elements of household heating systems based on wood-fired fireplaces are typical heat exchangers. Currently, fireplace inserts are fabricated mainly of gray iron with flake graphite in pearlitic matrix.

EU directives concerning emissions of flue gases to atmosphere force manufacturers of fireplace inserts to seek new solutions aimed at improvement of operating performance (heat exchange rate) of fireplace inserts leading thus to reduction of the quantity of burnt wood and the relating emissions to atmosphere.

Operating performance of a fireplace insert is decisive for interior temperature and warm-up rate. High temperature in rooms heated by fireplaces evidences ability of the insert to absorb heat from combustion chamber and transfer it efficiently to the ambient air [1–2].

Studies on improvement of thermal performance of fireplace inserts should be carried out in two directions. The first option consists in application of new materials with higher thermal conductivity. The second is employment of innovative solutions aimed at intensification of interception of heat from fireplace inserts made of traditional materials. This paper concerns the possibility of using, for that purpose, coatings of materials with higher thermal conductivity [3].

Coatings on gray iron castings, depending on the desired service properties, may be applied by means of the casting method, overlay welding methods, or thermal spraying techniques. Papers [4, 5] describe a process of formation of superficial composite layers with the use of the casting method in order to improve resistance of castings to thermal shocks. Authors of the paper [6] used the PTA (Plasma Transferred Arc) method to apply nickel-based coating on a flake graphite iron casting in order to improve its resistance to oxidation.

The thermal spraying process is used to improve resistance to abrasive wear, corrosion, or oxidation. Studies dealing with improvement of thermal conductivity with the use of this very coating method are however scarce in literature of the subject, the fact being also noticed by authors of [7].

The aim of the study was to assess the possibility to improve thermal performance of a cast-iron heat exchanger by providing it with a coating of copper alloy (CuTi2Cr) deposited on substrate of gray cast iron with vermicular graphite in ferritic-pearlitic matrix.

2. The material and methodology

The material used in the present study were flat plates with dimensions of 280 mm × 240 mm × 5 mm cast of gray iron with vermicular graphite in ferritic-pearlitic matrix. The plates were cast in sand molds, and vermicularization of the material was carried out by means of the wire method using 4.5 m of CEDIFIL NCF 4800 wire per 350 kg of liquid metal. This allowed to obtain the assumed magnesium content in the cast iron on the level of 0.020–0.022% Mg.

The CuTi2Cr coating was applied to one side of plate castings with the use of the flame spraying method. Parameters of the spraying process are listed in Table 1. Thickness of the deposited coating remained within the range of 140–200 µm.

Table 1.
Parameters of the CuTi2Cr coating flame spraying process

Parameter	Value
Oxygen pressure	0.6 MPa
Oxygen flow rate	27 l/min
Acetylene pressure	0.15 MPa
Acetylene flow rate	17 l/min
Air pressure	0.65 MPa
Wire feeding rate	Knob in “slow” position
Torch inclination angle	60°
Torch–surface distance	170 mm

Calorimetric measurements were carried out on the experimental set-up shown in Fig. 1, designed and constructed in the Department of Foundry and Welding, Rzeszów University of Technology, based on analysis of solutions used to construct welding calorimeters of the prior art [8–10]. The heat carrier used in the experiment was water with temperature of (85 ± 2)°C. The examined CuTi2Cr-coated plate of vermicular graphite cast iron was mounted in the calorimeter in such way that (Fig. 2) the coated surface reproduced one wall of the hot water chamber (hot chamber), while the surface without coating constituted the adjacent wall of the cold water chamber (cold chamber). The measurement was started at the moment when with the cold chamber already filled with water at temperature (10 ± 2)°C, the hot chamber was filled with water at temperature (85 ± 2)°C. Throughout the measured time, uniformity of temperature distribution in both chambers was ensured by means of agitation. The measurement methodology did not account for the energy introduced to the system by the agitation process as low-speed agitators were used.

(a)

(b)

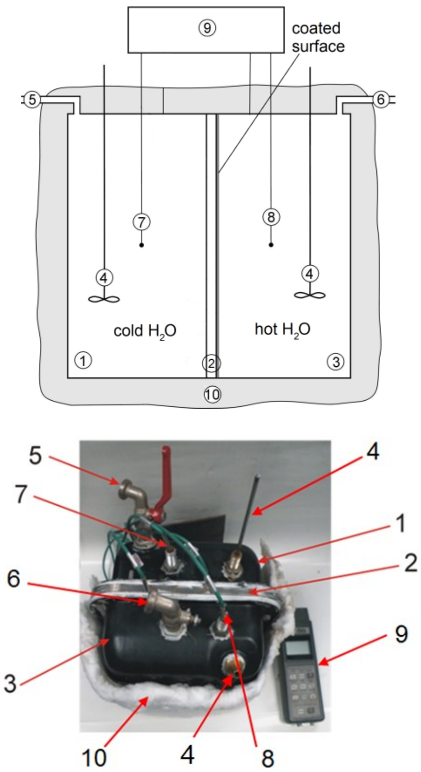


Fig. 1. (a) Schematic diagram and (b) a view of the set-up for heat flow rate measurements: 1 — cold water chamber, 2 — vermicular graphite iron plate casting, 3 — hot water chamber, 4 — agitators, 5 — cold water supply port, 6 — hot water supply port, 7 — cold water chamber thermocouple, 8 — hot water chamber thermocouple, 9 — digital thermometer, 10 — thermal insulation

Water temperature in both of the two water chambers was measured with the use of thermocouples connected to multi-channel digital thermometer HD 9016. In the course of the test, the time interval required to rise temperature of cold water up to the level of 40°C was measured.

The quantity of heat introduced to the cold water chamber was determined from the formula

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

where ΔQ denotes the quantity of heat intercepted by water in the cold chamber, J; m_w — mass of water in cold chamber, kg; c_w —

specific heat of water, $J\cdot(kg\cdot°C)^{-1}$; and ΔT — increase of water temperature in the cold chamber, °C.

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

$$\Phi = \Delta Q/\Delta t, \qquad (2)$$

where Φ denotes the rate of heat flow from the hot chamber to the cold chamber, kJ/s (kW); Q — quantity of heat intercepted by the hot water chamber, kJ; and Δt — the measured time interval after which water in the cold chamber reached the required temperature, s.

3. Test results and analysis

Microstructure of the test plate cast of gray iron with vermicular graphite in ferritic-pearlitic matrix is shown in Fig. 2.

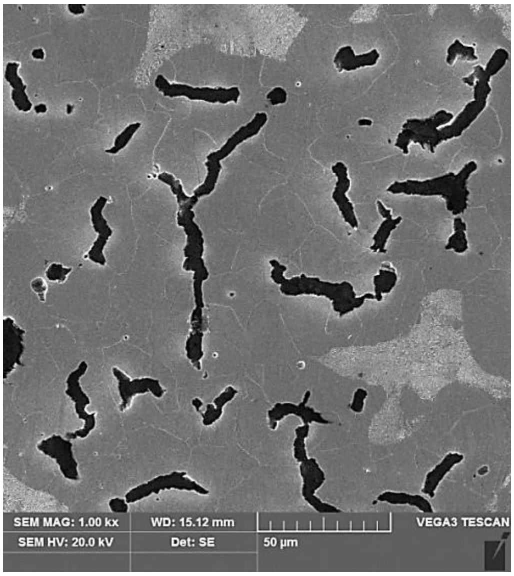


Fig. 2. Microstructure of the plate casting used in the study. Ferrite (dark), pearlite (light), vermicular graphite. Etched in 4% HNO_3

A view of the cross-section of the vermicular graphite iron plate with CuTi2Cr coating applied to its surface is presented in Fig. 3.

The obtained results indicate that the deposited CuTi2Cr coating is compact and its adhesion to substrate can be considered satisfactory. A singularity of the substrate microstructure in the superficial region is the disappearance of vermicular graphite and appearance of flake graphite precipitates. Such changes in the substrate material microstructure could be observed up to the depth ranging from 550 µm to 750 µm. These flake graphite precipitates were very fine which evidences high rate of cooling in this substrate material region which, however, was not high enough to enable crystallization of cementite eutectic.

A view of the microstructure and results of chemical analysis of the CuTi2Cr coating are presented in Fig. 4.

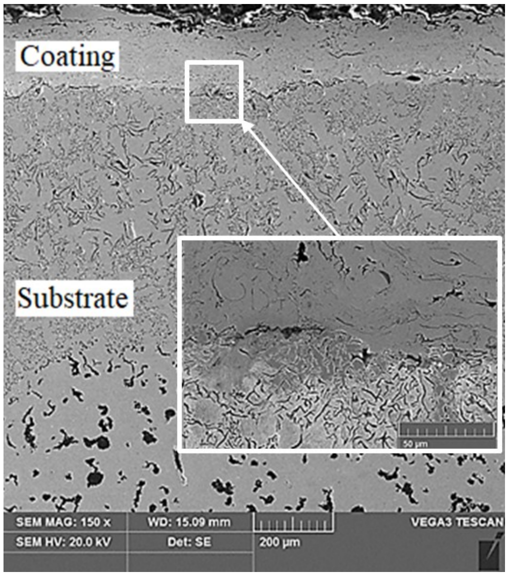
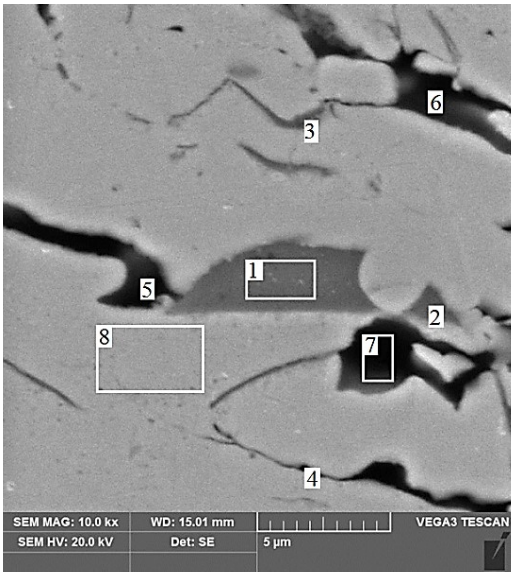


Fig. 3. A cross-section of the plate vermicular graphite iron casting with flame-sprayed CuTi2Cr coating. Etched in 4% HNO_3



Point	O	Ti	Cr	Cu
1	35.89	31.70	12.63	19.77
2	32.12	33.45	12.34	22.09
3	13.58	14.34	2.97	69.10
4	11.38	15.27	2.99	70.36
5	7.02	10.92	1.49	80.57
6	6.60	10.75	0.40	82.25
7	6.28	9.75	0.88	83.09
8	0.99	1.25	0.51	97.26
Element content, % wt.				

Fig. 4. Microstructure and results of analysis of chemical composition of the CuTi2Cr coating

The obtained results indicate that in the matrix of the coating material which is an alloy of copper with small addition of titanium (1.25% Ti) and chromium (0.51% Cr), there are very fine precipitates of oxides as the chemical composition analysis (in the micro-area marked 8) revealed presence of oxygen. In view of very small size of these fine features it was technically impracticable to perform microanalysis of their chemical composition. One can suppose that their chemistry is the same as this of the elongated oxides as these very small precipitates are frequently arranged along a line constituting continuation of longitudinal axis of the elongated precipitates (points 3 and 4) which turned out to be rich in titanium, oxygen, copper, and chromium. The oblong precipitates cross or are linked with more irregular features (points 6 and 7) characterized with different chemistry, being richer by about 10% in copper, poorer by about 5% in titanium, and containing two times less oxygen and about three times less chromium. In the coating material, precipitates in the form of polygons can be also found (points 1 and 2). They are characterized, in comparison with the above-described precipitate types, with several times lower content of copper, but on the other hand, several times larger content of titanium, oxygen, and chromium.

Results of measurement of the heat flow rate (thermal power) characterizing performance of vermicular graphite iron plate casting, with and without coating, are summarized in Table 2.

Table 2.
Results of measurements of the heat flow rate (thermal power) value for the vermicular graphite iron plate with and without CuTi2Cr coating on the heat-emitting side

Vermicular graphite iron plate casting	**Heat flux, kJ/s (Thermal power, kW)**
Without coating	0.681
With CuTi2Cr coating	0.752

The obtained results indicate that the value of the heat flow rate obtained for the cast-iron plate with CuTi2Cr coating applied on the heat-emitting side of the casting, is by about 10% higher compared to the value observed for plate having no coating.

4. Conclusions

Based on the performed study it has been found that a coating applied to surface of a plate casting of gray cast iron with vermicular graphite with the use of the flame spraying method and CuTi2Cr alloy wire as the sprayed material, is characterized with high compactness and good adhesion to substrate.

The employed spraying method resulted in appearance of super-fine oxide particles visible in the substrate material apart from those having the form of polygons as well as irregular and/or elongated precipitates. The features which could be subject to chemical microanalysis due to their size, differed in content of copper, titanium, chromium, and oxygen.

One effect of the employed coating application method were changes in microstructure of superficial regions of the substrate material, caused by thermal effect of both the flame and the jet of molten particles of the coating material.

It has been found that a 140–200 μm-thick coating of CuTi2Cr alloy applied to the heat-emitting surface of the model heat exchanger, which was a 5-mm thick plate cast of gray cast iron with vermicular graphite, resulted in an increase of value of the heat flow rate (thermal power) characterizing the exchanger in test conditions where the heat-carrying medium initial temperature was (85 ± 2)°C.

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