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Improvement of Resistance of Cast-iron Heat Exchangers to High-temperature Corrosion

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Abstract

The paper discusses the possibility of improving resistance of heat exchangers made of gray cast iron with flake graphite to high-temperature corrosion by providing them with metallic coatings. A metallic coating containing 76.9% Ni, 19.8% Cr, 1.7% Si, 0.9% Fe, and 0.9% Mn was applied by means of the plasma spraying method and subjected to cyclically variable thermal loads in the atmosphere of solid fuels combustion products (oxygen, sulfur, chlorine, and sodium). In a 30-day thermal load test held at temperature 500°C it has been found that thickness of the metallic coating decreased from the initial $(240 \pm 6) \mu\text{m}$ to $(231 \pm 6) \mu\text{m}$. The depth to which sulfur, chlorine, and sodium penetrated the coating was about 30 μm . Increased oxygen content occurred along the whole coating depth. In the coating area adjacent to the substrate surface, the content was twice as high compared to this observed in the initial coating material. Although presence of oxygen was found within the whole depth of the coating, i.e. $(231 \pm 6) \mu\text{m}$, no signs of susceptibility of the sprayed metallic layer to separation from substrate of gray cast iron with flake graphite were found.

Keywords: Heat exchangers, Metallic coating, Resistance to high-temperature corrosion

1. Introduction

Heat exchangers, such as fireplace inserts or heating furnaces with water circuit are fabricated mainly from cast iron as either monoblocks or assembled modular structures [1]. In the course of operation of such heat exchanger, its surface absorbing heat from combustion gases is exposed to high-temperature gas corrosion. The corrosion is an effect of exposure to elements such as oxygen, sulfur, chlorine, and sodium, present in gases. As a result of cyclical thermal load occurring in the atmosphere of combustion gases, scale is formed on surfaces of heating furnace inserts. Low compactness of the scale creates favorable conditions for intensification of corrosion processes [2]. Compactness of scale

depends on chemical composition of alloys. Numerous authors note that scales comprising a layer of chromium oxide are characterized with good protective properties [3, 4].

Earlier studies on corrosion resistance of unalloyed gray cast iron with flake graphite carried out in the atmosphere of air at temperature 500°C for a period of 30 days disclosed formation of a degraded material layer with thickness of about 35 μm , whereas the oxygen penetration depth was about 1200 μm . The tests carried out in the atmosphere of air in the environment containing sulfur, sodium, and chlorine disclosed creation of a degraded material layer with depth of 150 μm , while the sulfur, sodium, and chlorine penetration depth was about 1500 μm .

Corrosive effect of flame and combustion gases on walls of heat exchangers constituting components of boilers in power-

generating systems is mitigated by application of protective coatings [5, 6]. The aim of the present study was to demonstrate the possibility to extend the service life of cast-iron heat exchangers by application of metallic coatings.

The paper presents an assessment of susceptibility of a metallic coating material rich in nickel (about 77%) and chromium (about 20%) to penetration with sulfur, chlorine, sodium, and oxygen from combustion gases in view of possible blockage of access of the elements to the substrate surface by the coating and reduced depletion of its thickness.

2. Research material and methodology

The material used for the study were four plates (130 mm × 80 mm × 4 mm) of gray cast iron with flake graphite, provided with mounting holes $\phi = 3$ mm. The plates were given metallic coating on all of their surfaces. The surface of the cast-iron substrate was degreased with acetone and cleaned by blasting with abrasant (EFK930 alumina with grain size 125–180 μm) in the air stream supplied under pressure of 6 bar. The process was carried out manually by positioning nozzle face at a distance of about 1000 mm from plate surfaces. The process was carried out manually in KCW-1200-1150+FCPd abrasive blasting machine. The value of the height parameter S_t (defined as the distance between the line of peaks and the line of valleys) on surface of substrate plates prepared this way was $S_t = 31.5 \mu\text{m}$.

The material used for the coating was a metallic powder with properties given in Table 1. The process of plasma spraying the specimens used in the study was carried out on a robotized Sulzer Metco system, equipped with IRB 2400 robot (ABB) and F4-MB-HBS plasma gun (FST) cooperating with Twin-120-A/H powder feeders volumetrically supplying the plasma gun with powder.

Table 1.

Shape, size, and chemical composition of the plasma sprayed metallic powder

Shape	Size, μm	Fraction, %
Spherical	31–42	55
	10–31	35
Nodular	18–55	10
Chemical composition: 76.7% Ni, 19.8% Cr, 1.7% Si, 0.9% Fe, 0.9% Mn		

The spraying process was carried out with the use of the following parameters: F4-MB-HBS gun translation rate — 160–180 mm/s; current intensity — 600 A; plasma-generating gases — Ar (55–60 l/min) and H₂ (4–5 l/min); powder carrier gas — Ar 3–4 l/min, number of coating layers — 15; powder supplying parameters — feeder disc speed 10%, mixer speed 5%; plasma gun-sprayed element distance — 110 mm; cooling gas type: air at pressure of 2 bar.

One specimen was retained for examination in the condition without thermal load. Three other specimens were placed within the chamber of furnace adapted for burning solid fuels characterized with the combustion gas temperature of 500°C. Specimens were placed on a hanger which was then mounted in the furnace (Figure 1). The test was continued for 30 days.



Fig. 1. A view of specimens after a 30-day test. Note the deposit of solid combustion products

The fuel-burning furnace was equipped with a system for monitoring the chemical composition of combustion gases. The chemical composition analysis revealed presence of gases containing oxygen, sulfur, chlorine, and sodium.

The thickness of the metallic coating on specimens in the initial condition and after exposure to thermal load in the atmosphere of combustion gases was assessed on metallographic sections cut out in the plane perpendicular to the substrate surface with the use of VEGA XMH scanning electron microscope (TESCAN) at $\times 200$ magnification. Ten measurements were taken for each specimen. The presented results are averages of values from individual measurements.

Susceptibility of the coating material to penetration with sulfur, chlorine, sodium, and oxygen was tested with the use of the same scanning microscope equipped with INCA x-act adapter for chemical composition microanalysis (Oxford Instruments). The test included point-like analysis of areas containing discontinuities which could constitute paths for diffusion of sulfur, chlorine, sodium, and oxygen. The analysis was performed in three regions (a), (b), and (c) along the coating thickness (Figure 2).

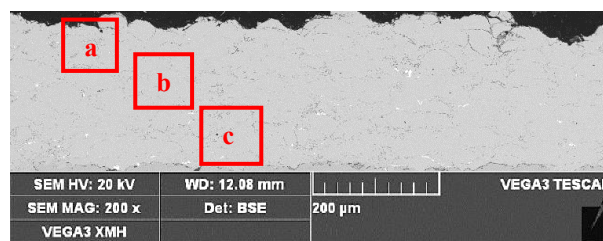


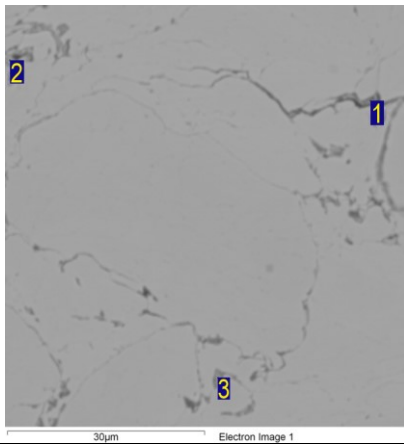
Fig. 2. Discontinuity-containing areas (a), (b), and (c) along the coating thickness in which the point-like chemical composition analysis was performed

3. Research results

Results of the research indicate that as a consequence of thermal load exerted in presence of combustion gases, the coating thickness decreased from the value of $(240 \pm 6) \mu\text{m}$ (in the as-deposited condition) to $(231 \pm 6) \mu\text{m}$.

Results of chemical analysis of the coating material in its initial condition suggest presence of oxides in the boundary areas between particles forming the coating, as shown in Figure 3. It

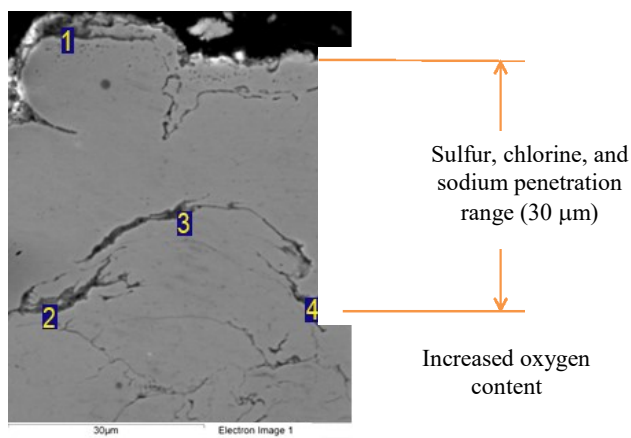
can be supposed that oxides were preset already on surfaces of spraying powder grains.



Spectrum	O	Cr	Si	Fe	Mn	Ni
1	5.83	19.35	1.14	2.01	1.47	to balance
2	5.72	19.36	1.13	1.90	0.99	to balance
3	3.00	19.29	1.10	2.85	1.12	to balance

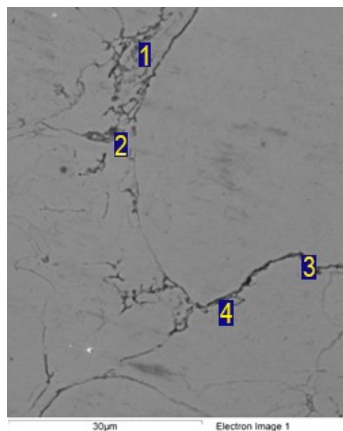
Fig. 3. Results of material chemical composition analysis in boundary regions between particle forming the coating. Presence of oxygen suggest occurrence of oxides

Results of assessment of susceptibility of the coating material to penetration with sulfur, chlorine, sodium, and oxygen in conditions of cyclically variable thermal loads are presented in Figures 4–6.



Spectrum	O	Na	Si	S	Cl	Cr	Mn	Fe	Ni
1	33.68	0.26	3.08	2.40	0.52	14.40	-	1.41	to balance
2	27.57	0.22	1.04	0.21	0.24	20.43	3.24	0.67	to balance
3	25.69	0.12	0.69	0.27	0.05	19.85	6.48	0.59	to balance
4	12.95	-	-	0.05	0.08	20.02	1.16	0.68	to balance

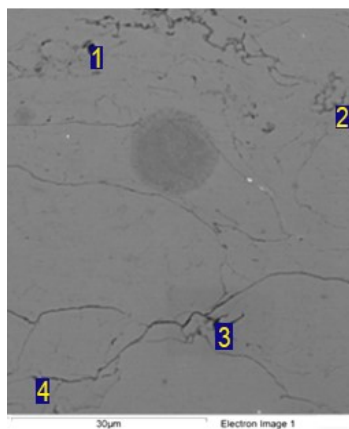
Fig. 4. Results of the search for presence of sulfur, chlorine, sodium, and oxygen in superficial layer (a) of coating



Absence of sulfur, chlorine, and sodium. Locally increased oxygen content.

Spectrum	O	Si	Cr	Mn	Fe	Ni
1	16.81	1.12	13.71	4.21	0.71	to balance
2	20.74	0.85	19.63	2.68	0.60	to balance
3	16.40	1.03	19.90	6.56	-	to balance
4	17.84	0.86	88.12	4.96	0.57	to balance

Fig. 5. Results of the search for presence of sulfur, chlorine, sodium, and oxygen in the middle region (b) of the coating depth



Absence of sulfur, chlorine, and sodium. Locally increased oxygen content.

Spectrum	O	Si	Cr	Mn	Fe	Ni
1	17.21	11.31	15.02	0.87	0.62	to balance
2	15.95	0.97	18.46	4.48	1.09	to balance
3	17.45	0.41	16.35	24.86	1.01	to balance
4	11.45	0.83	20.29	5.38	1.48	to balance

Fig. 6. Results of the search for presence of sulfur, chlorine, sodium, and oxygen in region (c) of coating adjacent to substrate

Results of examination of the coating after thermal load in conditions of exposure to combustion gases show that penetration of sulfur, chlorine, and sodium occurs in the superficial region of the coating up to a depth of about 30 μm. Elevated oxygen content was observed over the whole coating depth. In the coating regions adjacent to the substrate surface, the content was twice as high compared to this in the coating initial condition. No susceptibility of the coating to separation from cast-iron substrate was found which is a proof of satisfactory bonding between the substrate and the coating.

To demonstrate the possibility to improve resistance of the cast iron used for heat exchangers to high-temperature corrosion, results of preliminary tests have been compared to those obtained in the course of the test carried out as a part of the present study (Table 2).

Table 2.

Results of tests aimed at determination of the degraded material layer thickness and penetration depths for sulfur, chlorine, sodium, and oxygen due to soaking at temperature 500°C for 30 days in the atmosphere of combustion gases

	Material variant	
	w/o coating	w. coating
Degraded layer thickness	~ 150 μm	9 μm
Sulfur penetration depth	~ 1,500 μm	30 μm
Chlorine penetration depth	~ 1,500 μm	30 μm
Sodium penetration depth	~ 1,500 μm	30 μm
Oxygen penetration depth	~ 1,500 μm	231 μm

The obtained results indicate that application of metallic (Ni-Cr) coating onto surface of flake graphite cast iron specimens has efficiently reduced the thickness of the degraded material layer as well as the depth of sulfur, sodium, chlorine, and oxygen penetration resulting from interaction of combustion gases.

4. Summary

The obtained results indicate that application of a metallic coating containing high fraction of nickel (about 77 %) and chromium (about 20%) onto surface of a cast-iron heat exchanger

exposed to contact with combustion gases, would increase its service life by preventing access of elements intensifying the high-temperature corrosion process.

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