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Properties of Arc-Sprayed Coatings from Fe-based Cored Wires for High-Temperature Applications

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Abstract. Equipment of a thermal power plant is subjected to high temperature oxidation and wear. This raises operating costs through frequent repair of worn parts and high metal consumption. The paper proposes a possible solution to this problem through arc spraying of protective coatings. Cored wires of the Fe-Cr-C basic alloying system are used as a feedstock. Additional alloying by Al, B, Si, Ti and Y allows one to create wear- and heat-resistant coatings, which are an attractive substitute of more expensive Co- and Ni-based materials.

INTRODUCTION

Various parts in power engineering and metallurgy are exposed to gas corrosion and wear. Corrosion protection of parts and surfaces by means of thermally sprayed (TS) coatings is one of the rapidly developing fields of surface engineering. Arc spraying (AS) is one of the most cost-effective methods for coating formation. [1]. The coating of a metastable austenite structure is of particular interest due to low alloying cost and high wear resistance owing to the synergetic effect of transformation from austenite to martensite [2]. Fe-Cr-Al alloys are traditionally used for protection against gas corrosion in the form of both the bulk material and coatings [3, 4]. It is an attractive substitute of significantly more expensive Co- and Ni-base materials. Alloying a Fe-Cr-Al alloy by B increases the wear resistance of the alloy by forming reinforcing carboboride phases [5]. Addition of yttrium is favorable for protection against gas corrosion and wear for the following reasons. Firstly, Y-containing Fe-Cr-Al alloys showed good oxide adherences at high operation temperatures under thermal cycling [6]. Secondly, Y protects alloying elements from burnout during spraying, due to high Y affinity to oxygen. The aim of the study is to analyze wear- and heat-resistant properties of coatings from Fe-based cored wires.

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EXPERIMENTAL DETAILS

ASME 1020 steel specimens with the dimensions of 30x20x3 mm and 10x10x50 mm were used. The coating thickness was 0.4 mm and 1.5 mm correspondingly. The first type of coatings was used for the evaluation of the heat resistance, and the second type was used for wear test. An Active Arc Spraying gun (AAS), UWI, Ekaterinburg, Russia [7], was used (spraying distance 100 mm, gas inlet pressure 0.34 MPa for air and 0.32 MPa for propane, traverse velocity 200 mm/s, current, A / voltage, V 180/28 and 250/30 for wear- and heat-resistant coatings, respectively). 1.5Cr8Ti2Al cored wire, 1.6 mm in diameter, was taken as a feedstock in the tests up to 200 °C. It is a metastable austenite alloy, which is used to increasing wear resistance by arc spraying [8]. Two Cr13Al5B5 cored wires, 2.0 mm in diameter, namely AAS and AAS-Y, were used for high temperature tests. The composition of the second wire differs by alloying with yttrium (0.7 wt%). The Y content in the wire was designated according to the neural network model, which was developed in [9] with respect to arc spraying.

For the 1.5Cr8Ti2Al coatings, the studies were as follows:

- micro hardness was measured by a PMT-3 device (LOMO, St. Petersburg, Russia); the surface of the 1.5Cr8Ti2Al coatings was additionally rolled down by the ball-on-plate reciprocating technique, with a ball diameter of 10 mm, ball steel E52100 ASTM (65 HRC), a traverse speed of 0.16 m/s, a stroke of 125 mm, a friction path of 5 m and an axial load of 100 N;
- the coating structure was studied by a MET 2 microscope (Altami, St. Petersburg, Russia), a DRON-3.0 X-ray diffractometer (Bourevestnik Inc., St. Petersburg, Russia) in Fe- and Co-Kα radiation, a Philips SEM 525 scanning electron microscope (FEI, Hillsboro, USA);
- two-body abrasive wear tests were carried out by the pin-on-plate reciprocating technique; corundum abrasive paper with a grain size of up to 150 μm was fixed on the plate, and the as-sprayed specimen was fixed in a holder; the test conditions included a full friction path of 60 m, a pin velocity of 0.16 m/s, a specific load of 1 MPa and a work surface area of 10×10 mm.

For the Cr13Al5B5 coatings, the studies were as follows:

- the amount of oxygen in the coating was measured by melting the coating in inert gas flow by an ON-900 analyzer (Eltra, Haan, Germany);
- the porosity of the coatings was determined by metallography on the transverse sections using SIAMS 700 commercial hardware and software (SIAMS, Ekaterinburg, Russia);
- the adhesion strength of the coatings was determined by the separation of a conical pin from the coated washer [10]; heat resistance was evaluated by weight-loss measurements in accordance with GOST 9.312, 100 h, air, 700 °C;
- high-temperature corrosion testing was performed in an alumina tube furnace, 550 °C, 168 h; 20×20 mm ASME 1020 steel specimens were cut out, and an 18-mm-diameter circle was covered with approximately 1 g of KCl salt; the furnace environment was purged with 1.5 l/min of air with the addition of water vapor reaching 12% of specific humidity;
- microhardness measurements were performed by a Leica VMHT device (Walter Uhl, Aßlar, Germany);
- the phase composition on the coating surface was determined by an XRD-7000 X-ray diffractometer, Cr-Kα radiation (Shimadzu, Kyoto, Japan); the microchemical structure and the composition of the coatings was studied by a Vega II XMU scanning electron microscope (Tescan, Brno, Czech Republic) equipped with an INCA Wave 700 wavelength dispersive X-ray spectrometer and an INCA Energy 450 XT energy dispersive microanalyzer (Plastomertiya collective use center, Institute of Engineering Science, Ural Branch of RAS, Russia);
- the microstructure was investigated by a SEM Philips XL30 scanning electron microscope with energy dispersive X-ray (EDX) microanalysis of the cross section, and the phase composition was assessed by X-Ray diffractometry (XRD, Empyrean, PANalytical, Co-Kα radiation) of the coating surface. Phase identification was performed using the PANalytical X'Pert HighScore Plus software using the ICDD JCPDF-2 database (International Centre for Diffraction Data, Newtown Square, PA, USA).

RESULTS AND DISCUSSION

Coatings from 1.5Cr8Ti2Al cored wire

The metallographic analysis of transversal microsections after etching reveals some representative colors and tints of the structural components: white stripes alternate with gray ones. A fairly good connection at the coating-substrata border is revealed; the oxide layers are thin, with rare thickenings and pores. Fragment pieces of the coating microstructure are 10 to 50 μm in size. The SEM analysis of the coating surface demonstrates that the white fields contain Fe (bal.), Cr (6 to 10 wt%) and a negligible quantity of titanium. These metal fragments represent a solid solution of chromium in austenite and in martensite. Gray fragments represent a maximum concentration of alloying elements, wt%: Cr (10-12); Ti (2-3), Fe (bal.). These gray areas are likely to be complexes of carbides and oxides, due to the spraying process. The XRD analysis shows that the phase structure is based on metal (70 vol%). It consists of martensite and retained austenite in a 50/50 ratio, vol%. The other share of the structure includes titanium carbide, chromium carbide and oxides. Thus, the light fragments comprise a metal base; the gray ones comprise carbides, namely, Ti and Cr carbides; the dark ones comprise Fe oxides. The measurements of the coating surface in the ball-on-plate test show that microhardness rises after rolling. It is accompanied by a reduced amount of austenite in the metal matrix as per X-ray analysis. After a two-body wear test, the amount of austenite drops largely (Table 1). The wear tests have shown that the wear resistance is 3 to 5 times as high as that for 20Kh13 solid wire.

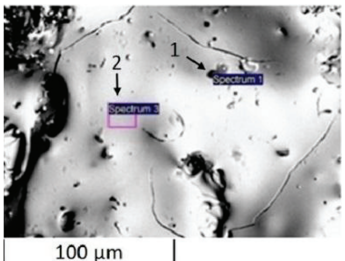
TABLE 1. Phase transformation in the deposition after surface loading

Type of test		Microhardness 600 $HV_{0.1}$	Austenite/martensite ratio, vol%
Before loading		600	50/50
Ball-on-plate	1 rolling	770	40/60
	2 rollings	880	30/70
Pin-on-plate, mode 1			20/80

Coatings from Cr13Al5B5 cored wire

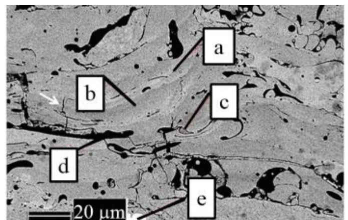
The oxygen content in the AAS-Y coating (1.3 wt%) is 1.8 times less than that in the Y-free coating. This result coincides with the side data from [11], according to which the oxygen content in the AS coatings is halved by the introduction of rare-earth metals into CW. The porosity of the AAS-Y coating is 2.8%, the maximum pore size is 24.2 μm, the minimum pore size is 1.2 μm, and the number of pores smaller than 10 μm is 97.4%, their total area and volume being 73.1% and 50.4%, respectively. The porosity of the coating from Y-free FeCrBAl wire is 3.5%, a with a similar pore distribution. In the AAS-Y coating, adhesion strength is 43 MPa, and this is 1.2 times as high as that of the Y-free coating. According to the surface analysis (Fig. 1), the AAS-Y coating consists of an iron α-phase (solid solution of Fe-Cr-B, enriched with carbon) with reinforcing phases – Fe_2B, $(Fe,Cr)_2B$ borides and $(Fe,Cr)_2(B,C)$ carboborides. Y-Al oxides are found in the AAS-Y coating at the borders and within the structure areas. The zones pointed as (a-e) have been detected by EDX microanalysis in the cross section of the AAS-Y coating (Fig. 2). Various greyscale colored striations (a, b) differ in the content of Al and Y. In particular, darker striations have a major amount of Al and Y. Small cracks have been detected along the boundary of such zones (white arrow). Some small dark-grey drop-like inclusions (c) are rich in Y and Al. Pores (d) are present in the coating. At the coating-substrate interface, several white, long inclusions sized about 100 μm are observed (e). These big inclusions are Ni-rich, which may be caused by the surface preparation method. The EDX microanalysis of the overall image of the coating after corrosion test demonstrates the following (Fig. 3). A homogeneous thin corrosion-product layer is observed on top of the coating. The topmost corrosion-products layer (a) is rich in metal oxides, probably, in the form of chromates, ferrates and aluminates of potassium. A thin porous layer lies between the corrosion products and the coating (b). The EDX spot analysis in the pores (c) indicates the presence of Cr, Y and Al. The high amount of Fe probably belongs to the coating. This porous morphology might be a precipitation zone of borides, which was subjected to selective corrosion of Cr, as the XRD analysis suggests. This type of morphology may be caused by chlorine-induced corrosion. Chlorine can selectively react with alloying elements and precipitates like borides and carbides, forming volatile chlorides that leave the surface in form of vapor, resulting in a porous area. The formed chlorides then migrate toward the surface where the higher partial pressure of oxygen makes them deposit in the form of oxides [12]. The chromium oxide in the layer lying on the top of the porous area (c) was probably originated in this way. Several inclusions of different shapes and sizes have been detected (d). The presence of Al and Y oxides is revealed in these inclusions. The specific weight loss for the AAS-Y coating is 0.54 g/(m^2·h). It is an order of magnitude smaller than that for T11 and T122 pearlite/martensite-ferrite steels (10 to 80 g/(m^2·h)) and similar to the TempaloyA-1 and TP310 austenite steels (0.1 to 4 g/(m^2·h)), which are commercial boiler materials [13, 14]. The microhardness of the AAS-Y coating is 1222±52 HV0.05 and 1111±64 HV0.3. The wear of AAS-Y is compared with the 150Cr8Ti2Al cored wire coating and ASME 1020 solid steel. The comparison yields the following results:

- it is by 20% lower than the AAS coatings from the yttrium-free wire. This result coincides with the side data concerning the effect of REM additives on the wear resistance of the Fe-based coating at two-body wear [11];
- it is less than half that of the 150Cr8Ti2Al coating due to the formation of complex carbides like (Fe,Cr)2(B,C) in the coating; it is an order of magnitude smaller than in case of ASME 1020 steel.



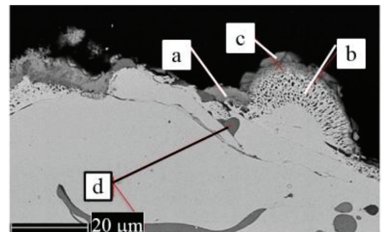
Element, content		O	Al	Si	Cr	Y	Fe
Spectrum 1	wt.%	38.2	37.4	0.3	4.6	11.1	8.3
Spectrum 2	wt.%	-	2.4	0.7	9.9	11.1	87.0

FIGURE 1. A SEM image of the coating surface and EDS elemental analyses of details 1 and 2. (Si exists as a charge component).



Element, content		B	O	Al	Y	Cr	Ni	Fe
Spectrum a	wt.%	4.68	1.37	3.79	0.39	8.57	--	81.19
Spectrum b	wt.%	--	20.8	37.96	25.48	2.75	--	13.01
Spectrum c	wt.%	--	13.62	13.03	67.38	1.10	0.76	4.12
Spectrum d	wt.%	--	23.31	38.52	30.93	1.44	1.27	4.53
Spectrum e	wt.%	--	--	--	3.79	--	92.94	3.27

FIGURE 2. The microstructure of the AAS-Y coating and EDS quantitative elemental analyses of the indicated micro-structural details



Element, content		O	Al	Cl	K	Cr	Y	Fe
Spectrum a	wt.%	22.6	2.00	0.33	3.41	8.69	--	62.97
Spectrum b	wt.%	2.92	1.94	0.23	0.33	1.54	0.55	92.49
Spectrum c	wt.%	22.67	0.51	0.41	43.46	28.86	--	4.08
Spectrum d	wt.%	20.15	35.3	--	--	0	0.97	5.53

FIGURE 3. The cross section of the AAS-Y coating after high-temperature corrosion test. See details in the text

CONCLUSION

Lean-alloyed cored wires for spraying coatings have been developed. The coatings can be used under wear- and heat-resistant conditions ranging from 20 to 700 °C.

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