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Operational factors of new flux cored wires of the Fe-C-Si-Mn-Cr-Ni-Mo system for surfacing of protective plates of shearer cutting drums

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Abstract. Evaluation of the joint effect of the chemical composition of flux cored wires on the wear and hardness of the deposited layer was carried out using mathematical-statistical methods, allowing the influence of the chemical composition of the flux cored wires on the performance of the weld layer of the mining equipment to be revealed. According to the results of the multifactor correlation analysis, the dependences of the hardness of the deposited layer and its wear resistance on the mass fraction of elements included in the flux cored wires composition of the Fe-C-Si-Mn-Cr-Ni-Mo system were determined. The obtained dependences are used to predict the hardness of the deposited layer and its wear resistance when the chemical composition of the weld metal is changed. New, protected by patents of the Russian Federation, flux cored wires of the system Fe-C-Si-Mn-Cr-Ni-Mo for surfacing the mining equipment were developed.

1. Introduction

In the Russian Federation the main flux-cored wires are the wires of Fe-C-Si-Mn-Cr-Ni-Mo system, type A and B according to the IIW classification [1], which increase the wear-resistant surfacing of mining equipment. For this purpose foreign-made DT-SG 600 F wire by DRATEC (Germany), OK Tubrodur 15.52, OK Tubrodur 58 O/GM by ESAB based on the same doping principles [5-8] are widely used.

In works [9-23] carried out at Siberian State Industrial University, the influence of the introduction of various elements into the flux cored wire of the Fe-C-Si-Mn-Cr-Ni-Mo system on the operational durability of the metal layer obtained during surfacing was determined. This paper presents the study of the influence of change in the concentration of various elements in the developed wires in the Fe-C-Si-Mn-Cr-Ni-Mo system on wear and hardness of the weld metal.

2. Methods of research

The surfacing was carried out by ASAW-1250 welding tractor using the produced flux cored wire on plates of steel 09G2S. Wire production was carried out on a laboratory machine. The diameter of the wire is 6 mm, the sheath is made of St3 tape. Powder materials were used as a filler: iron powder of PZhV1 grade according to GOST (State Standards) 9849-86, ferrosilicon powder FS 75 grade according to GOST 1415-93, high-carbon ferrochrome powder FKh900A according to GOST 4757-91, carbon ferromanganese powder FMn 78(A) according to GOST 4755-91, PNK-1L5 nickel powder according to GOST 9722-97, ferromolybdenum powder FMo60 according to GOST 4759-91, ferrovanadium powder FV50U 0.6 grade according to GOST 27130-94, PK-1U cobalt powder according to GOST 9721-79, tungsten powder PVN TU 48-19-72-92.

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The dust from gas cleaning plant of aluminum production with the following chemical composition was introduced in the composition of a number of wire samples instead of amorphous carbon, mass. %: $Al_2O_3 = 21-46$; F = 18-27; $Na_2O = 8-15$; $K_2O = 0.4 - 6\%$; CaO = 0.7 - 2.3; $SiO_2 = 0.5 - 2.5$; $Fe_2O_3 = 0.5 - 2.5$; Fe2.1-3.3; $C_{tot} = 12.5-30.2$; MnO = 0.07-0.9; MgO = 0.06-0.9; S = 0.09-0.19; P = 0.10-0.18. The chemical composition of the deposited metal was determined by X-ray fluorescence method on XRF-1800 spectrometer and atomic emission method on DFS-71 spectrometer. The measurement of the hardness of the studied samples was performed according to the Rockwell method in accordance with the requirements of GOST 9013-59. The metallographic study of microsections was carried out using OLYMPUSGX-51 optical microscope in a bright field in the magnification range \times 100 – 1000 after etching the surface of the samples in a 4% nitric acid solution. The grain size was determined according to GOST 5639-82 with an magnification of \times 100. The dispersion of martensite was evaluated by comparing the structure with the standards of the respective scales and sizes of martensite needles with the data of table No. 6 GOST 8233-56. The study of longitudinal samples of the deposited layer for the presence of non-metallic inclusions was carried out according to GOST 1778-70. The polished surface was studied at magnification \times 100 using LaboMet-1I metallographic microscope.

The abrasion rate of the deposited layer of prototypes was determined by carrying out wear tests on 2070 SMT-1 machine using a disk – wear block scheme with the following parameters: measurement range of the shaft rotation rate of the lower sample (range A) 75–750 min ⁻¹; friction torque measurement range (range I) $1 - 10 \text{ N} \cdot \text{m}$.

3. Results and discussion

Two series of samples with similar chemical composition and grain size of austenite but with different chromium content (table 1) were selected for the study – the first series (samples A5-A24) with more than 3% of chromium (3.94 - 7.1%) and the second series (samples I1-I16) with less than 2% of chromium (1.32 - 1.83%), with the same structure – martensite (table 2). To assess the combined effect of the chemical composition of the flux cored wires on the wear and hardness of the deposited layer, mathematical and statistical methods were applied, which make it possible using known methods to identify patterns of change in the resulting index depending on the behavior of various factors [24-26]. Figures 1-9 show the effect of various elements in the deposited layer using the tested flux cored wires on the hardness and wear separately for each of the series and the total for these series.

The obtained graphs indicate that the degree of influence of various chemical elements on the hardness of the deposited layer and the wear of the samples is different. Within the studied limits (both for each of the series, and on the general graph) carbon, silicon, manganese, chromium and molybdenum simultaneously improve the hardness of the deposited layer and reduce sample wear, vanadium has the same tendency for each series. Nickel increases hardness and wear. When choosing the optimal chemical composition for surfacing, tungsten and cobalt were introduced into the study of the influence of tungsten and cobalt on the properties of the deposited layer, it was found that the increase in the concentration of tungsten slightly increases the hardness of the weld metal, however, this reduces its wear resistance.

Cobalt also reduces hardness and wear. This is apparently due to the high-strength solid martensitic matrix, in which harder tungsten carbides are "embedded". The low viscosity of the matrix does not allow tungsten carbides to be kept on the surface, as a result the wear is carried out not according to the uniform surface abrasion scheme, but according to the scheme of chipping high-strength carbide particles from the matrix, resulting in the formation of cracks in the matrix contributing to additional its wear.

The introduction of cobalt to the mixture composition is apparently associated with obtaining a more viscous, but less solid matrix. In the case of the absence of solid particles of carbides embedded in the matrix, the effect of the introduction of cobalt is negative. The experiments indicated the

inexpediency of tungsten and cobalt introduction into the charge of the developed wires within the investigated limits.

Sample No.	С	Si	Mn	S	Р	Co	Cu	W	Cr	Мо	Ni	V
A5	0.4	0.72	0.84	0.037 (0.025	0.1	0.07	0.02	5.26	0.52	0.42	0.05
A6	0.45	0.8	0.77	0.044 (0.023	0.11	0.07	0.02	4.98	0.5	0.56	0.04
A7	0.27	0.78	0.77	0.042 (0.019	0.08	0.1	0.02	5.5	0.48	0.61	0.04
A8	0.38	0.62	0.8	0.038 (0.020	0.09	0.07	0.02	4.98	0.47	0.82	0.04
A9	0.19	0.77	0.61	0.054 (0.024	0.051	0.07	0.02	4.17	0.38	0.34	0.02
A10	0.19	0.63	0.65	0.056 (0.019	0.056	0.08	0.02	4.06	0.38	0.3	0.03
A11	0.2	0.59	0.61	0.049 (0.019	0.121	0.06	0.02	4.12	0.38	0.3	0.02
A12	0.2	0.64	0.6	0.058 (0.021	0.199	0.08	0.02	4.03	0.39	0.3	0.03
A13	0.26	0.78	1.49	0.033 (0.009	0.003	0.07	0.02	7.1	0.39	0.32	0.02
A14	0.22	0.73	1.38	0.029 (0.014	0.003	0.09	0.02	5.95	0.32	0.29	0.03
A15	0.26	0.75	1.23	0.034 (0.012	0.003	0.09	0.02	6.3	0.32	0.3	0.02
A16	0.26	0.75	1.16	0.033 (0.016	0.003	0.09	0.02	6.06	0.34	0.3	0.04
A17	0.13	0.56	0.91	0.033 (0.017	0.003	0.08	0.03	3.94	0.25	0.26	0.006
A18	0.17	0.61	1.2	0.033 (0.015	0.002	0.1	0.025	6	0.37	0.39	0.006
A20	0.1	0.49	0.92	0.033 (0.017	0.004	0.09	0.025	4.15	0.23	0.25	0.03
A21	0.19	0.54	1.15	0.031 (0.015	0.002	0.09	0.025	6.21	0.38	0.4	0.04
A22	0.23	0.67	0.94	0.029 (0.015	0.013	0.07	0.04	4.18	0.4	0.27	0.005
A24	0.205	0.78	1.01	0.030 (0.015	0.19	0.07	0.08	4.12	0.37	0.26	0.008
The average												
content of												
the element	0.24	0.68	0.95	0.038	0.02	0.06	0.08	0.03	5.06	0.38	0.37	0.03
in the 1 st												
series												
I1	0.24	0.19	0.93	0.036 (0.017	0.001	0.87	0.02	1.83	0.69	0.14	0.6
I2	0.25	0.27	0.96	0.033	0.01	0.001	0.09	0.08	1.65	0.68	0.33	0.6
I3	0.25	0.28	0.93	0.029 (0.014	0.001	0.06	0.02	1.67	0.57	0.54	0.58
I4	0.29	0.15	0.92	0.034 (0.012	0.001	0.06	0.05	1.65	0.6	0.65	0.59
15	0.23	0.12	0.85	0.033 (0.017	0.08	0.05	0.001	1.45	0.51	0.53	0.68
I6	0.21	0.23	0.89	0.031 (0.015	0.03	0.07	0.001	1.45	0.55	0.54	0.54
I7	0.17	0.18	0.85	0.029 (0.016	0.05	0.06	0.001	1.4	0.54	0.52	0.63
I8	0.17	0.28	0.91	0.032 (0.015	0.06	0.06	0.001	1.32	0.46	0.45	0.59
I13	0.22	0.18	0.64	0.031 (0.017	0.001	0.09	0.003	1.59	0.08	0.46	0.48
I14	0.21	0.23	0.73	0.033 (0.017	0.001	0.09	0.001	1.73	0.23	0.53	0.55
I15	0.22	0.2	0.84	0.035 (0.016	0.001	0.08	0.001	1.7	0.52	0.58	0.63
I16	0.21	0.19	0.79	0.033	0.02	0.001	0.09	0.001	1.62	0.77	0.59	0.61
The average												
content of												
the element	0.22	0.21	0.85	0.03	0.02	0.02	0.14	0.02	1.59	0.52	0.49	0.59
in the 2 nd												
series												

Table 1. The chemical composition of the weld metal (wt. %).

We should specially focus on the effect of chromium. When comparing the first and second series of casts, it was determined that the increase in the chromium concentration in the deposited layer in three times makes it possible to increase the hardness by approximately in 1.5 times and reduce wear by 45%.

Factors that have an impact on the studied indicator were identified for the analysis, and the most significant of them were selected (table 1, 2). After that, the initial information was checked for reliability, uniformity, and compliance with the law of normal distribution. Next, the mathematical

model of a multifactor system was built. Since in the above systems there are independent factor signs, a deterministic factor analysis is used.

According to the results of calculations, dependences were obtained, the adequacy of which to the actual values was checked in terms of the average approximation error.

Sample No.	Structure	Austenite grain size	HRC	Wear, g/r		
A5	Martensite	7	49	0.000014		
A6	Martensite	6.5	52	0.0000056		
A7	Martensite	6	50	0.000071		
A8	Martensite	6.5	52	0.000014		
A9	Martensite	6.5	44.5	0.000071		
A10	Martensite	6.5	42.5	0.000039		
A11	Martensite	6.5	42.5	0.000044		
A12	Martensite	6.5	37	0.000073		
A13	Martensite	7	55	0.000028		
A14	Martensite	7	41	0.000055		
A15	Martensite	7	45	0.0000074		
A16	Martensite	7	45	0.000034		
A17	Martensite	6.5	40	0.000028		
A18	Martensite	6	45	0.000054		
A20	Martensite	6.5	38	0.000142		
A21	Martensite	6	48	0.000055		
A22	Martensite	6	43	0.000033		
A24	Martensite	6.5	42	0.00003		
aver	age	6.53	45.08	0.00004433		
I1	Martensite	6.5	41	0.000029		
I2	Martensite	6.5	40	0.000037		
I3	Martensite	5.6	40	0.0000358		
I4	Martensite	5.6	41	0.0000359		
I5	Martensite	6.5	25	0.000136		
I6	Martensite	6	21	0.000165		
I7	Martensite	5.6	21	0.000115		
I8	Martensite	5.6	21	0.0000888		
I13	Martensite	6.5	20	0.00015		
I14	Martensite	6	25	0.000134		
I15	Martensite	6	29	0.00015		
I16	Martensite	6	28	0.000092		
aver	age	6.03	29.33	0.000097		

Table 2. Characteristics of the structure, grain size, wear and hardness of the deposited samples.





Figure 1. The effect of carbon on hardness and wear.





Figure 2. The effect of silicon on hardness and wear.





Figure 3. The effect of manganese on hardness and wear.





Figure 4. Effect of chromium on hardness and wear.





Figure 5. The effect of nickel on hardness and wear.





Figure 6. The effect of molybdenum on hardness and wear.





Figure 7. The effect of vanadium on hardness and wear.





Figure 8. The effect of cobalt on hardness and wear.





Figure 9. The effect of tungsten on hardness and wear.

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The dependences of hardness of the deposited layer and its wear resistance on the mass fraction of the elements making up the flux cored wires of the Fe–C–Si–Mn–Cr–Mo–Ni–V–Co system obtained as a result of the analysis performed are as follows:

The hardness of the weld layer:

$$\label{eq:HRC} \begin{split} HRC &= 17.03 + 19.49 \cdot C - 2.27 \cdot Si - 9.43 \cdot Mn + 4.25 \ Cr + 15.67 \cdot Mo + 8.35 \ Ni - 33.56 \ Co + 12.41 \cdot Cu \\ &+ 191.12 \cdot W - 10.69 V - 22.45 \cdot S + 46.16 \cdot P \ (approximation \ error \ is \ 1.09\%); \end{split}$$

The wear rate of the weld layer on the samples:

 $W = 0.000106 - 0.000268 \cdot C + 0.0000179 \cdot Si - 0.0000447 \cdot Mn + 0.0000108 \cdot Cr - 0.0000984 \cdot Mo + 0.000036 \cdot Ni + 0.000121 \cdot Co - 0.0000362 \cdot Cu - 0.000647 \cdot W + 0.000186 \cdot V - 0.000229 \cdot S + 0.000722 \cdot P$ (approximation error is 2.94%).

Analysis of the obtained data formed the basis for the development of the chemical composition of new flux cored wires protected by patents of the Russian Federation [27, 28].

It should be particularly noted that the choice of a flux cored wire for the process should be made on the basis of economic prerequisites, in particular the operational period of the equipment.

4. Conclusion

New cored wires of the system Fe–C–Si–Mn–Cr–Mo–Ni for surfacing of mining equipment were developed, and patented in the Russian Federation.

According to the results of the multifactor correlation analysis, the hardness dependences of the deposited layer and its wear resistance on the mass fraction of elements included in the flux cored wires of the Fe–C–Si–Mn–Cr–Mo–N system were determined. The obtained dependences are used to predict the hardness of the deposited layer and its wear resistance when the chemical composition of the weld metal is changed.

Testing in the mines of Kemerovo region of the protective plates of the shearer cutting drums JOY4LS20, surfaced with the developed cored wire (RF patent 2641590), showed an increase in durability by 19.3%, compared to similar plates welded with DRATEK. At the same time, the amount of coal produced by the mining equipment surfaced with the developed flux cored wire for the period of testing is 253,654 tonnes, and application of plates welded with DRATEK wire – 204,698.7 tonnes of coal.

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