Study of the properties of flux cored wire based on dust from gas cleaning plant of ferrochrome for surfacing on the cutting bodies of tunneling machines

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Abstract. The possibility of producing flux-cored wires based on dust from gas cleaning plant of aluminum production, silicon and aluminum powders (as a reducing agent) and gas cleaning dust from ferrochrome production (as a reducible component – chromium oxide) was studied. In the laboratory conditions samples of flux-cored wires were produced, surfacing, hardness measurement, abrasion rate and metallographic studies were performed.

1. Introduction
Improvement in the performance of the cutting bodies of tunneling machines working in difficult conditions is an important factor for increasing the volume of production, as well as saving equipment service life and reducing economic costs. The development of new materials that can increase the wear resistance of such parts and the use of technologies for their restoration is a very important task. In this paper, the possibility of making flux-cored wires based on dust from gas cleaning plant of aluminum production, silicon and aluminum powders (as a reducing agent) and dust from gas cleaning plant of ferrochrome production (as a reducible component – chromium oxide) is considered.

2. Methods of research
The manufacture of the wire was carried out on the laboratory installation for the manufacture of flux-cored wires according to the technology with passage through dies. As a reduced substance dust from gas cleaning plant of ferrochrome production with chemical composition, wt. % Cr₂O₃ = 22.5; SiO₂ = 15.5; CaO=0.4; MgO=31.1; Al₂O₃ = 5.4; FeO₂ = 6.0; C= 6.2; S=1.2, as a reducer the powders were used: silicon KR-1 according to GOST (State Standards) 2169-69, wt. %: Si = 98.00; Fe = 0.7; Al = 0.7; Ca = 0.6%; aluminum PAP-1 according to GOST 5494-9, wt. % Fe = 0.5; Si = 0.4; Cu = 0.05; Mn = 0.01; and dust from gas cleaning plant of aluminum production, wt. %: Al₂O₃ = 21-46.23; Fe = 18-27; Na₂O = 8-15; K₂O = 0.4-6; CaO = 0.7-2.3; SiO₂ = 0.5-2.48; Fe₂O₃ = 2.1-3.27; C_tot = 12.5-30.2; MnO = 0.07-0.9; MgO = 0.06-0.9; S = 0.09-0.19; P = 0.1-0.18 as carbonaceous material. The dispersion of such material allows a good mixing with the metal component of the charge of flux-cored wire to be carried out. Wire production was carried out on the laboratory machine. The diameter of the obtained wire is 5 mm, the coating is made of St3 tape.

Surfacing was carried out on ASAW – 1250 welding tractor. The satisfactory quality of the roll bead was obtained in the following surfacing conditions: for wires with the addition of dust from gas cleaning plant of aluminum (carbon) production – current 620A, voltage 32V, welding speed 28m/h;
for wires with silicon – current 620A, voltage 32 V, deposition speed 25 m/h; for wires with aluminum – current 550A, voltage 28, deposition speed 12 m/h.

The chemical composition of the deposited metal and the obtained slag crusts was determined by X-ray fluorescence method on XRF-1800 spectrometer according to GOST 28033 – 89 and atomic emission method on DFS-71 spectrometer according to GOST RISO 14284-2009.

The study of the microstructure was carried out using OLYMPUS GX-51 optical microscope after etching the samples surface in 2% solution of nitric acid.

3. Results and discussion

The chemical composition of the deposited metal layer and slag crusts is presented in tables 1 and 2.

| Table 1. The chemical composition of the deposited metal layer. |
|----------------------|-----------------|----------------|----------------|-----------------|-----------------|-----------------|----------------|----------------|
| Sample No. | C   | Si  | Mn  | P   | S   | Cr  | Ni  | Cu  | Mo  | V   | Al  | Co  | Nb  | Ti   |
| 50        | 0.12 | 0.43 | 1.1  | 0.012 | 0.05 | 0.43 | 0.064 | 0.06 | 0.006 | 0.006 | 0.015 | 0.009 | 0.005 |
| 51        | 0.17 | 0.57 | 1.35 | 0.012 | 0.09 | 0.48 | 0.07  | 0.05 | 0.01  | 0.004 | 0.004 | 0.02  | 0.003 | 0.004 |
| 52        | 0.2  | 0.5  | 1.1  | 0.014 | 0.09 | 0.42 | 0.07  | 0.05 | 0.01  | 0.004 | 0.004 | 0.01  | 0.002 | 0.004 |
| 53        | 0.26 | 0.6  | 1.17 | 0.016 | 0.10 | 0.37 | 0.07  | 0.06 | 0.01  | 0.01  | 0.01  | 0.02  | 0.003 | 0.004 |
| 54        | 0.12 | 0.9  | 1.28 | 0.018 | 0.11 | 0.71 | 0.07  | 0.1  | 0.01  | 0.002 | 0.002 | 0.02  | 0.002 | 0.004 |
| 55        | 0.1  | 1.04 | 1.31 | 0.02  | 0.09 | 0.53 | 0.07  | 0.07 | 0.01  | 0.02  | 0.006 | 0.02  | 0.001 | 0.004 |
| 56        | 0.1  | 1.15 | 1.25 | 0.017 | 0.10 | 0.6  | 0.06  | 0.06 | 0.01  | 0.01  | 0.01  | 0.02  | 0.001 | 0.005 |
| 57        | 0.09 | 1.34 | 1.11 | 0.019 | 0.08 | 0.53 | 0.07  | 0.07 | 0.01  | 0.02  | 0.01  | 0.02  | 0.002 | 0.004 |
| 58        | 0.08 | 0.76 | 1.79 | 0.014 | 0.08 | 0.43 | 0.08  | 0.05 | 0.01  | 0.004 | 0.01  | 0.02  | 0.002 | 0.004 |
| 59        | 0.12 | 0.67 | 1.42 | 0.014 | 0.10 | 0.49 | 0.07  | 0.05 | 0.01  | 0.004 | 0.02  | 0.02  | 0.001 | 0.004 |
| 60        | 0.1  | 0.61 | 1.14 | 0.013 | 0.08 | 0.4  | 0.07  | 0.05 | 0.01  | 0.004 | 0.03  | 0.02  | 0.01  | 0.004 |
| 61        | 0.12 | 0.83 | 1.66 | 0.018 | 0.07 | 0.43 | 0.07  | 0.07 | 0.01  | 0.02  | 0.07  | 0.02  | 0.001 | 0.004 |

| Table 2. The chemical composition of slag crusts. |
|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| No.     | FeO   | MnO  | CaO  | SiO2  | Al2O3 | MgO  | Na2O  | K2O  | S   | P   | F   | Cr2O3 |
| 50      | 2.05  | 6.99 | 28.71| 44.02 | 6.97  | 9.01 | 0.39  | Orc. | 0.16 | 0.01 | 0.54 | 0.72 |
| 51      | 2.41  | 6.79 | 27.05| 45.61 | 9.07  | 5.34 | 0.65  | 0.41 | 0.27 | 0.01 | 0.63 | 0.74 |
| 52      | 2.28  | 6.67 | 26.7 | 44.29 | 9.16  | 5.01 | 0.66  | 0.37 | 0.27 | 0.01 | 0.82 | 0.67 |
| 53      | 2.12  | 6.74 | 27.17| 45.9 | 9.74  | 4.39 | 0.67  | 0.39 | 0.28 | 0.01 | 0.82 | 0.49 |
| 54      | 1.83  | 6.82 | 27.31| 46.21 | 9.42  | 5.19 | 0.58  | 0.41 | 0.27 | 0.01 | 0.43 | 0.77 |
| 55      | 1.58  | 6.58 | 26.96| 44.73 | 9.83  | 5.8  | 0.57  | 0.39 | 0.27 | 0.01 | 0.39 | 0.8 |
| 56      | 1.52  | 6.58 | 26.75| 44.31 | 9.99  | 5.15 | 0.55  | 0.38 | 0.26 | 0.01 | 0.4  | 0.72 |
| 57      | 1.25  | 6.63 | 25.97| 45.1 | 10.52 | 4.89 | 0.55  | 0.39 | 0.28 | 0.01 | 0.42 | 0.56 |
| 58      | 1.94  | 6.71 | 25.69| 45.68 | 8.47  | 6.07 | 0.62  | 0.4  | 0.28 | 0.01 | 0.44 | 1.06 |
| 59      | 2.12  | 6.59 | 25.45| 45.69 | 8.28  | 6.6  | 0.4  | 0.27 | 0.01 | 0.39 | 1.16 |
| 60      | 1.93  | 6.65 | 26.14| 46.27 | 8.51  | 5.48 | 0.6  | 0.43 | 0.28 | 0.01 | 0.5  | 0.99 |
| 61      | 1.91  | 6.45 | 26.46| 47.37 | 8.65  | 6.21 | 0.63  | 0.43 | 0.29 | 0.01 | 0.48 | 1.07 |

The use of carbon as a reducing agent in the processes of surfacing leads along with an increase in the chromium content in the weld metal to an increase in the carbon content, which explains the decrease in the volume fraction of ferrite in the structure. In addition, the size of martensitic needles is significantly reduced to a size of 8–15 μm and the primary size of austenitic grain (figure 1, sample 51).

The use of silicon powder as a reducing agent in the surfacing wire practically does not change the microstructure of the weld metal with an increase in its concentration from 11.12 to 27.27%. In this case, the microstructure of the deposited layer is characterized by coarse-needle martensite inside the former austenite grains, and coarse ferrite precipitates along the boundaries of these grains (figure 2). In addition, when silicon powder is used for reducing processes of chromium from its oxides, a higher amount of non-metallic inclusions, which are silicates and point oxides, is observed in the surfacing structure in comparison with the usage of aluminum for surfacing.
With an increase in the concentration of the reducing aluminum powder from 7.78 to 27.27% in a wire, the microstructure in the deposited layer changes due to the structural components size reduction: martensite, ferrite. So, for the maximum aluminum content in the flux-cored wire (27.27%), the presence of fine-needle martensite with needles up to 10 µm in size and thin ferrite intermediate layers (4-7 µm) along the boundaries of the former austenite grains (figure 3) is noted in the structure of the deposited metal.

When considering the deposited metal layer using various types of reducing agents – carbon, silicon (Kp-1 powder) and aluminum (PAP-1 powder) with their content in the mixture 27-28% (samples 51, 57, 61).

It can be stated that for all three deposited samples made using tested flux-cored wires with various reducing agents, a martensitic-troostite structure is characteristic with the release of free ferrite along the boundaries of the primary austenite grains. The most inhomogeneous structure of the deposited metal with a large size of needle-like martensite crystals corresponds to surfacing using powdered silicon as a reducing agent. The maximum size of martensitic needles can reach 25 µm and ferrite layers, having the Widmanstätt morphology, 25-30 µm.

![Figure 1](image)

**Figure 1.** The microstructure of the weld metal depending on the content of the reducing agent (carbon) in the cored wire, × 200.

The introduction of aluminum flux-cored wires into the composition helps to obtain the most fine-grained structure of the deposited layer, including fine-needle martensite (up to 10 µm), primary austenite grain (20-60 µm) and ferrite layers along the austenite grain boundaries (figure 3, sample 61).

Taking into account the results of metallographic analysis and determination of hardness of the deposited layers (table 3) using tested flux-cored wires, it is preferable to use carbon and aluminum for surfacing.
Figure 2. The microstructure of the weld metal depending on the content of the reducing agent (silicon) in the cored wire, × 200.

Thus, the analysis of the deposited layers microstructure makes it possible to recommend the tested cored wires for the production of wear-resistant coatings on steel products, which include powdered carbon reducing agent or aluminum powder in the amount of at least 27%.

Evaluation of the influence of the cored wire chemical composition based on the dust from gas cleaning plants of ferrochrome and aluminum production on the degree of wear and hardness of the deposited layer was carried out by means of correlation analysis. To carry out the analysis the factors that affect the studied indicator were identified and the most significant of them were selected.

Studies showed that otherwise things being equal the absorption of chromium depends on the fill factor of the cored wire (figure 4). Hardness always correlates with wear (figures 5-7), and with the increase in chromium concentration the surface wear decreases (figure 7).
Figure 3. Microstructure of the weld metal depending on the content of the reducing agent (aluminum) in the cored wire, × 200.

Table 3. Hardness and sample wear.

| No. | Weight before abrasion, g | Weight after abrasion, g | Weight loss, g | Number of rotations | Wear, g/r | HB     |
|-----|---------------------------|--------------------------|----------------|---------------------|-----------|--------|
| 50  | 78.8                      | 78.48                    | 0.32           | 3574                | 0.000090  | 175.11 |
| 51  | 92                        | 91.58                    | 0.42           | 3300                | 0.000127  | 158.89 |
| 52  | 106.08                    | 105.6                    | 0.48           | 3240                | 0.000148  | 169.11 |
| 53  | 53.54                     | 53.18                    | 0.36           | 3580                | 0.000101  | 167.11 |
| 54  | 73.27                     | 72.88                    | 0.39           | 3730                | 0.000105  | 171.67 |
| 55  | 39.23                     | 38.92                    | 0.31           | 3530                | 0.000088  | 140.67 |
| 56  | 81.98                     | 81.7                     | 0.28           | 3814                | 0.000073  | 164.78 |
| 57  | 56.25                     | 55.75                    | 0.5            | 3370                | 0.000148  | 152.36 |
| 58  | 98.25                     | 97.77                    | 0.48           | 3805                | 0.000126  | 133.22 |
| 59  | 102.05                    | 101.65                   | 0.4            | 3800                | 0.000105  | 147.78 |
| 60  | 86.33                     | 85.81                    | 0.52           | 3530                | 0.000147  | 132.11 |
| 61  | 56.1                      | 55.48                    | 0.62           | 3800                | 0.000163  | 164.89 |

Figure 4. The dependence of the absorption of chromium on the fill factor of the flux cored wire.
Figure 5. Effect of carbon content on hardness and wear.

Figure 6. Effect of silicon content on hardness and wear.

Figure 7. Effect of chromium content on hardness and wear.
According to the results of calculations, dependencies were obtained, the adequacy of which to the actual values was checked by the average approximation error:

$$\varepsilon = \frac{1}{m} \sum_{i=1}^{m} \left| \frac{Y_i - \tilde{Y}_i}{Y_i} \right| \cdot 100,$$

(1)

According to the results, where $m$ is the number of observations; $\tilde{Y}_i$ – the calculated value of the resulting indicator; $Y_i$ – the actual value of the resulting indicator.

Dependencies of the hardness of the deposited layer and its wear resistance on the mass fraction of the elements making up the flux cored wires obtained as a result of the performed analysis:

$$H_b = 368.504 + 283.917 \cdot C + 58.821 \cdot Si - 27.909 \cdot Mn - 1407.34 \cdot S - 95.985 \cdot Cr - 1899.96 \cdot Ni + 1566.943 \cdot Cu - 4454.3 \cdot V + 222.375 \cdot Al - 5200.13 \cdot Nb \ (\text{approximation error } 0.64\%).$$

Weight loss during wear – wear rate = - 0.000509 + 0.000648 $\cdot$ C + 0.000101 $\cdot$ Si - 0.000099 $\cdot$ Mn + 0.001911 $\cdot$ S + 0.000496 $\cdot$ Cr + 0.008647 $\cdot$ Ni - 0.0017007 $\cdot$ Cu - 0.002118 $\cdot$ V + 0.0021128 $\cdot$ Al + 0.0022335 $\cdot$ Nb (approximation error 0.21).

4. Conclusions
1. The absorption of chromium in the weld layer is completely dependent on the fill factor of the flux cored wire.
2. 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 the elements, that make up the flux cored wire, were determined. The dependences obtained can be used to predict the hardness of the deposited layer and its wear resistance when the chemical composition of the weld metal is changed.
3. Microstructure analysis of the of the deposited layers allows the tested flux-cored wires to be recommended for the production of wear-resistant coatings on steel products, which include powdered carbon reducing agent (dust from gas cleaning plant of aluminum production) or aluminum powder in the amount of at least 27%.

References
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