Computer-assisted design of flux-cored wires

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Abstract. The algorithm and description of the AlMe-WireLaB software for the computer-assisted design of flux-cored wires are introduced. The software functionality is illustrated with the selection of the components for the flux-cored wire, ensuring the acquisition of the deposited metal of the Fe-Cr-C-Mo-Ni-Ti-B system. It is demonstrated that the developed software enables the technologically reliable flux-cored wire to be designed for surfacing, resulting in a metal of an ordered composition.

1. Introduction

Due to their high workability in surfacing processes, flux-cored wires are the parent material when it is required to surface the alloy with special properties [1-3]. The Fe-Cr-C-Mo-Ni-Ti-B alloying system is of interest as the basis for the development of abrasion-resistant alloys with a thermo-resistant structure at temperatures of up to 550 °C [4, 5]. Yet such a structure can be acquired with optimal boron and carbon alloying on the one hand responsible for solid phase formation, and, on the other hand, for excessive increases in the metal’s brittleness [6, 7].

To obtain this optimum, the components’ content and the filling factor of the flux-cored wire are required to be recalculated many times. To automatise these operations, special software is required to account for specific mass (g/mm³) of an element, its content in the metal band or powder and the alloy transfer effervescive. Thus, our objective was to develop the software enabling flux-cored wire design to acquire the ordered composition of the deposited metal with the best working properties.

2. Materials and methods

With the developed AlMe-WireLaB software, the flux-cored wire was designed to ensure the following deposited metal composition, % wt.: 3–3.2 C; 12.5–13.0 Cr; 1.8–2.1 Mo; 1.0–1.4 Ni; 1.2–1.5 Ti; 0.4–0.5 B; and Fe – the remainder. The coating of the flux-cored wire of 3.0 mm in diameter was formed from steel strap Sv-08kp, which is 12 mm wide and 0.5 mm thick [8]. The core of the designed flux-cored wire consisted of aluminothermic chrome, ferromolybdenum, sodium silicofluoride, commercial nickel and silver graphite powders as well as the titanium diboride powder.

Arc surfacing on the steel of grade 20 with the designed flux-cored wire was performed in the shielding gas (argon) with direct current of the reversed polarity. The weld fabrication characteristics of the wires were controled by recording oscillograms of the welding current and arc voltage during the reference samples' surfacing with the computer-assisted control method and the analog-to-digital converter ‘LA-20USB’. The chemical composition of the deposited metal was specified with the spark optical emmission spectrometer ‘PMI MASTER Pro’. The deposited metal structure was studied with
electron microscopy (scanning dual beam electron-ion microscope FEI Versa 3D).

3. Flux-cored wire calculation methods

The aim of these calculation methods was to specify the flux-cored wire composition that, at a certain filling factor of the wire, will ensure the ordered composition of the deposited metal. To calculate the composition of the flux-cored wire core, the following data are required:

- the composition of the deposited metal;
- the rated chemical composition of the wire specified as a function of the deposited metal composition, adjusted for alloy oxidation during surfacing and for the base metal share in the deposited metal;
- the percentage ratio of the core and coating masses in the flux-cored wire (filling factor);
- the chemical composition of the materials used to produce the wire (viz. metal band, metal powders, ferroalloys, minerals, and other components).

The calculation is performed on the basis of required wire mass $M_{f\text{cw}}$ (kg) and diameter $D_{f\text{cw}}$ (mm). To attain the required content of the elements in the deposited metal, a somewhat larger amount of alloying powders should be added to the wire content in accordance with their alloy transfer effervescives.

The alloy transfer effervescives from the wire into the deposited metal accounting for the losses in the weld fire point due to oxidation, vaporization, transition into the slag etc., are chosen with an approximation, using known data (Table 1); then they are experimentally ascertained and corrected [9].

Table 1. Experimental values of alloy transfer effervescives from the wire into the deposited metal during arc welding with a consumable electrode in the shielding gas (argon)

| Alloying elements | C  | Cr  | Mo | Ti  | Ni |
|-------------------|----|-----|----|-----|----|
| Alloy transfer effervescive | 0.86 | 0.76 | 0.7 | 0.3 | 0.7 |

When calculating, it is necessary to consider that the alloy transfer effervescives depend on the surfacing procedure and mode, mostly on the welding current rate and arc voltage, the component's content in the wire, the presence of the deoxidizing agents, powders' granulation in the core of the flux-cored wire, and the alloying system of the deposited metal [10].

The flux-cored wire content is calculated for 100 g of the wire. The required amount of the component via which the alloy is added can be calculated as:

$$p = \frac{[X]_e \cdot 100}{b},$$

where $p$ is the mass of the flux-cored wire core component, g; $[X]_e$ is the required amount of the calculated alloy in the wire core, g; and $b$ is the content of the considered alloy in the added component, % wt.

As long as accompanying alloys can be added to any core component except for pure powders of metals, graphite and chemical compounds, their amount is accounted for and calculated as:

$$d = \frac{P \cdot c}{100},$$

(2)
where \( d \) is the accompanying alloy mass, g; \( c \) is the content of the accompanying alloy in the added component, % wt; and \( P \) is the mass of the added component, g.

It should be borne in mind that the accompanying alloys are also added to the metal band. If the total amount of impurities exceeds the prohibitive limit, the material adding excessive impurities should be substituted by the component with their minimal content or by the pure metal powder.

Next, the preliminary calculation of the filling factor of the flux-cored wire (\( K'_p \)) is made:

\[
K'_p = \sum_{i=1}^{n} m_{kom}.
\]

(3)

where \( m_{kom} \) is the mass fraction of all the core components with an allowance for the accompanying impurities.

The geometrical parameters (i.e. thickness and width) of the band for the coating of the experimental flux-cored wire are chosen according to the data in Table 2.

Next, the powder mixture is prepared (50–100 g) and the wire is produced by 6x or 4x drawing-down. Then, a 100 mm piece is cut from the middle part of the wire and weighed with at least a three-place balance, and then the core is removed and the coating mass is specified.

### Table 2. Filling factors of the flux-cored wire provided by different bands

| Wire diameter, mm | 3.6 | 3.0 | 2.5 |
|-------------------|-----|-----|-----|
| Band width, mm    | 15  | 12  | 10  |
| Band thickness, mm| 0.8 | 0.5 | 0.4 |
|                   | 0.8 | 0.5 | 0.4 |
|                   | 0.8 | 0.5 | 0.4 |
|                   | 0.8 | 0.5 | 0.4 |
|                   | 0.8 | 0.5 | 0.4 |
| Filling factor, \( K_3 \) | 0.28–0.3 | 0.38–0.4 | 0.52–0.55 |
|                   | 0.22–0.25 | 0.33–0.33 | 0.4–0.42 |
|                   | 0.18–0.2 | 0.28–0.3 | 0.33–0.38 |

Next, core mass \( M'_e \) is calculated by formula 3.15:

\[
M'_e = M'_p - M'_w,
\]

(4)

where \( M'_p \) is the mass of the flux-cored wire piece; and \( M'_w \) is the mass of the flux-cored wire coating.

With the values obtained, the actual filling factor (\( K'_p \)) is then calculated:

\[
K'_p = \frac{M'_e}{M'_p}
\]

(5)

If \( K'_p > K'_p \), then they are evened out with neutral additives (for ferrous alloys – iron powder). To eliminate cavitation, 1.5–2 % of sodium silicofluoride (Na-SiF\(_6\)) is added to the mixture consisting mainly of ferrous alloys [11].

If \( K'_p < K'_p \), the calculation is refined. For this purpose, first, the specific mass of the cogged core (\( \rho_s \)) is calculated:

\[
\rho_s = \frac{M'_e}{\pi (d - 2s)^2 \cdot L}
\]

(6)

where \( d \) is the FCW diameter; \( s \) is the thickness of the flux-cored wire coating; and \( L \) is the length of the flux-cored wire piece (i.e. 100 mm).
With known $\rho_s$, it is possible to calculate precisely the coating thickness ($s$) required to provide for the needed filling factor ($K^*_p$):

$$s = \frac{d}{2} \left( 1 - \sqrt{\frac{K_p}{K^*_p}} \right),$$

(7)

where factor $K_r$, dependent on the physical properties of the flux-cored wire components, is calculated as:

$$K_r = \frac{\rho_s}{\rho_o} \left( \frac{1}{K^*_p} - 1 \right) + 1,$$

(8)

where $\rho_o$ is the specific mass of the coating metal.

The coating thickness ($s$) should correspond to the nomenclature value of the manufactured metal bands. For this purpose, value $s$ is rounded upwards; this calculation refines filling factor $K^*_p$:

$$K^*_p = \frac{\rho_o}{d^2} \left( \frac{1}{4(d \cdot s - s^2)} \right)^{-1} + 1.$$

(9)

The band width ($h$) is calculated as:

$$h = 1.06 - \pi(D - s),$$

(10)

where $D$ is the drawing die diameter.

4. Description of the AlMe-WireLaB software

Development of the flux-cored wire ensuring the required chemical composition of the deposited metal requires reiterated calculations of the components’ content and geometrical parameters of the wire. To automate this calculation, the AlMe-WireLaB software was developed. Its algorithm is introduced in Figure 1.

The main interface window of the program shows the saved calculations list – block 1, which can be reviewed, edited, printed – block 7, or deleted. The design of the flux-cored wire starts with the button ‘add’. In the opened window, one can specify:

- name (at least four and no more than 200 characters);
- calculation type – ‘flux-cored wire’;
- flux-cored wire diameter in mm;
- flux-cored wire mass;
- mass units (kg or g);
- surfacing method.

To work with the created calculation, one should select it from the list. To enter the required composition of the deposited metal, select the required tab in the ‘Database menu’:

- ‘Elements database’ – contains the name and the specific mass ($g/mm^3$) of the element from the periodic system;
- ‘Material database’ – contains the compositions of the components used to produce the flux-cored wire.
If we know only the elemental composition, let us select the first database; if we know the mass fraction of the component added into the flux-cored wire, let us select the second database. To add a component to the window ‘source data’ – (algorithm block 2), one should point the cursor to its name and click the right mouse button – the line will be highlighted. Then the form ‘material parameters’ should be filled in with the component’s mass fraction and the button ‘add component’ should be pressed. If a component should be deleted from the table ‘source data’, one should select the line with its name and press the button ‘delete’ above. When the source data list is formed, press the button ‘introduce kp’. In block 3, the composition is recalculated taking into account transition coefficients of the alloying elements, which values are taken from the software database (Figure 2, a).

The flux-coated wire composition is configured by choosing source materials as per GOST standards (algorithm block 4).

For this purpose, in the tab ‘source data’, let us select the line with the alloy name and press the button ‘suggest’ (Figure 2, a). In the opened tab, we choose the mass fractions of the impurities that will be added to the wire together with the component. After the component is chosen from the list, we should click on the line ‘total’ of this component and press the button ‘add’ (Figure 2, b, c). After this, the selected component will replace the alloy in the source data table, and the flux-cored wire composition will be recalculated with provision for the impurities occurring in the wire together with the component. To specify the composition of the band from which the flux-cored wire coating will be formed, we should select it from the list ‘material database’ and press the button ‘add component’; the mass fraction, however, is not specified. After all, the alloys are replaced with the components and the coating material specification, we press the button ‘calculate’. Next, in block 5, the automated calculation is performed. The program opens the tab ‘calculated’, where the result of the performed calculation (algorithm block 6) is shown.

![Flow Chart](image.png)

**Figure 1.** The control-flow chart for the operation of the software for flux-cored wire design.
Figure 2. Alloy selection (а) and variants of components: ferrochrome (b) and aluminothermic chrome (c) with which it can be added to the flux-cored wire.

To compare the component composition of the calculated flux-cored wire with the source, we press the button ‘chemical composition’. The opened tab (Figure 3) shows the calculated and the ordered chemical composition and their divergencies from each other. The chemical elements specified in the source data are highlighted in green to separate them from the impurities.

Figure 3. The tab ‘chemical composition of the flux-cored wire’.

To reduce the impurity content in the flux-core wire, it is required to replace the components
excessively adding them with a component with minimal impurity content or to add chemically pure metal powder. To this end, this component is visually highlighted in the tab ‘calculated’; then we pass to the tab ‘source’, we highlight the line in the table with the component and press the button ‘delete’. Next, with the previously described algorithm of replacement, for example, ‘Cr’ — with aluminothermic chrome (Figure 2, a, c), and the remaining carbon – with ‘Silver graphite POL-2,’ we press the button ‘calculate’. Now, there should be no divergencies from the ordered composition (Figure 4). However, there may still be impurities (for example, Mn), added by the band. To reduce them, if it is possible, the iron powder is added to the filler, and the band thickness is reduced.

![Figure 4](image4.png)

**Figure 4.** The tab ‘chemical composition of the flux-cored wire after conversions’.

Next, according to the data in Table 2, the geometric parameters (i.e. thickness and width) of the band are chosen to produce the coating of the experimental flux-cored wire, the powder mixture is prepared (50–100 g), and the flux-cored wire is produced by 6x or 4x drawing-down. Then, with Equation (6), value $\rho_c$ is specified and entered in the program via form $q$, opened with the button ‘value $\rho_c$’.

The calculation results are shown in the tab ‘source’ (Figure 5) in line with the ordered band parameters. To print out the calculation results in a convenient form, we press the respective button – block 7.

![Figure 5](image5.png)

**Figure 5.** The calculation results.

The administration mode enables one to extend and to edit the database of materials and their properties as well as that of the alloy transfer effervescives.

5. **Confidence Rating**

According to the results of the calculation, 10 m of the flux-cored wire were produced. The filling factor estimation performed for several sections of the produced wire showed good convergence (i.e. no more than a 5% error) of the empirical and calculated values.
The acquired oscillograms of the welding current and arc voltage during surfacing indicate a stable drop transfer with a drop detachment frequency of 0.126 s, which means uniform melting of the flux-cored wire components.

The deposited metal structure (Figure 6) represents a carboboride eutectic composed of a solid solution of iron, iron-chrome carboborides, and titanium molybdenum carbides.

![Figure 6. Deposited metal microstructure (a) and chemical composition (b) in the segments of solid solutions and carbides.](image)

The spark optical emission spectrometer proved the ordered composition of the deposited metal.

6. Conclusions

Due to the introduction of the alloy transfer effervescives and the specific mass of the coggend core, the suggested method enables one to select, with maximum precision, the width and thickness of the band for the flux-cored wire coating in order to ensure the required filling factor.

The developed AlMe-WireLaB software, containing the wide appendable database of the alloy transfer effervescives of the core powder components, as well as a simple interface, facilitates the flux-cored wire design methods.

The functionality and reliability of the calculation methods and the software were proven by the fact that the arc surfacing with the designed flux-cored wire resulted in the formation of the deposited metal of the Fe-Cr-C-Mo-Ni-Ti-B system with the ordered composition.

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