

# Analysis of oxidation of self-baking electrodes (Soederberg electrodes) by means of three-dimensional model

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**Abstract.** The paper presents the methodology and results of the development of the temperature dependence of the oxidation speed of the self-baking electrode (Soederberg Electrodes) in the ore-thermal furnaces. For the study of oxidation, the working ends of the self-baking electrodes, which were taken out from the ore-thermal furnaces after their scabbings, were used. The temperature of the electrode surface by its height was calculated with the help of the mathematical model of heat work of self-baking electrode. The comparison of electrode surface temperatures with the speed of oxidation of the electrode allowed one to obtain the temperature dependency of the oxidation of the lateral electrode surface. Comparison of the experimental data, obtained in the laboratory by various authors, showed their qualitative coincidence with results of calculations of the oxidation rate presented in this article. With the help of the mathematical model of temperatures fields of electrode, the calculations of the sizes of the cracks, appearing after burnout ribs, were performed. Calculations showed that the sizes of the cracks after the ribs burnout, calculated by means of the obtained temperature dependence, coincide with the experimental data with sufficient accuracy.

## 1. Introduction

The self-baking electrodes are oxidized while operating ore-thermal furnaces. Their shape changes during oxidation of the self-baking electrodes, which affects their strength, distribution of the electric and magnetic fields, all process of metal melting. Therefore, the electrode oxidation process has a great practical value both when developing recipes of electrode masses of self-baking electrodes and when analyzing the constructive elements of the electrodes and the ore-thermal furnaces.

To estimate the impact of the form of the working end of the electrode on the processes occurring in furnaces, it is necessary to understand the process of its formation in the process of furnaces work. The process analysis inside the furnace is very difficult due to the high temperatures inside the oven, the presence of aggressive gases, the presence of electric arc and molten metal. Thus, it seems reasonable to use mathematical models of the electrode. To take proper account of the electrode oxidation, the mathematical model must include the temperature dependence of the oxidation rate of the lateral electrode surface.

The oxidation rate of carbon materials obtained under laboratory conditions cannot be directly used in mathematical models.

This article presents the methodology for calculating the oxidation rate of the side surface of self-baking electrodes during ferrosilicon smelting. The working ends of the self-baking electrodes, which were taken out from the ore-thermal furnaces after their scabbing and calculations of temperature fields



of self-baking electrodes were used as a data source to retrieve the temperature dependence of the electrode surface oxidation.

## 2. Oxidation calculation method

The electrode oxidation occurs on the surface, on which the electric arc burns [1-3]. The oxidation from the lateral surface of the electrode is related to its interaction with atmospheric oxygen over the furnace roof, with gases formed during combustion of the electric arc below the furnace roof.

The intensity of oxidation of the electrode surface is usually characterized by the mass rate of oxidation,  $g_k$  (kg/(m<sup>2</sup>·c) [1]. It is associated with the fact that the rate of chemical reactions depends on the electrode surface. As is well known, the rate of chemical reactions depends significantly on temperature [4]. Therefore, it is necessary to find the temperature dependency of the oxidation rate on the temperature of the electrode surface. It can be used in the mathematical model of thermal work of the self-baking electrode.

The interaction of gases and the furnace-charge with an electrode lateral surface occurs at high temperatures under a layer of furnace-charge and is extremely difficult for research. The experimental studies of oxidation of carbon [5] and graphite materials were carried out under laboratory conditions and cannot be applied to the self-baking electrodes. These works can be of only qualitative nature for the self-baking electrodes. Therefore, the temperature dependence of the oxidation rate of the electrode lateral surface was defined by using experimental data about the working ends of the electrodes, which were taken out from the ore-thermal furnaces after their scabbing. To this end, a series of measurements of the working ends of the electrodes with a diameter of 1.5 m after their scabbing was carried out. The edges of cracks in working ends of the electrodes, formed after melting ribs were used for calculations. They are a part of the lateral surface of the electrode and oxidize together with it. Therefore, the value of oxidation was assessed according to crack width.

20 cracks on 5 working ends of the electrodes were measured. Working ends of the electrodes were conditionally broken to elements by their height. The width value of the crack was taken as constant equal to the crack width in the centre of the element. So the value of a crack width was taken as constant and equal to the width of real cracks in the middle of the element.

The processing of the results of measurements allowed one to obtain average values of crack sizes at various points ( $\sigma < 10\%$ ) along the height of the ribs of the working end of the electrode. The amount of mass deleted from lateral electrode surface of was defined as follows:

$$g_k = \frac{l_k \rho}{2} \quad (1)$$

$g_k$  - the amount of mass, oxidated from the lateral electrode surface in the k-element, kg/m<sup>2</sup>;  $l_k$  - the statistically average width of cracks of the k-element of the electrode, m;  $\rho$  - density of electrode material, kg/m<sup>3</sup>.

From time to time, the electrode is moved into the furnace by the value of  $h_m$  with time step  $\tau_m$ . The working end of the electrode was divided conditionally into elements by its height. The levels of the temperatures near the surface of the electrodes is changed when the electrode moves to the furnace. After the movement into the furnace by the value of  $h_m$  the lateral electrode surface gets into the field of higher temperatures of gases and oxidates with a higher oxidation rate. For that reason, the time of element oxidation at a defined level is accepted to be equal to the time of moving electrode by the value of  $h_m$ .

$$\tau_k = \frac{h}{h_m} \tau_m \quad (2)$$

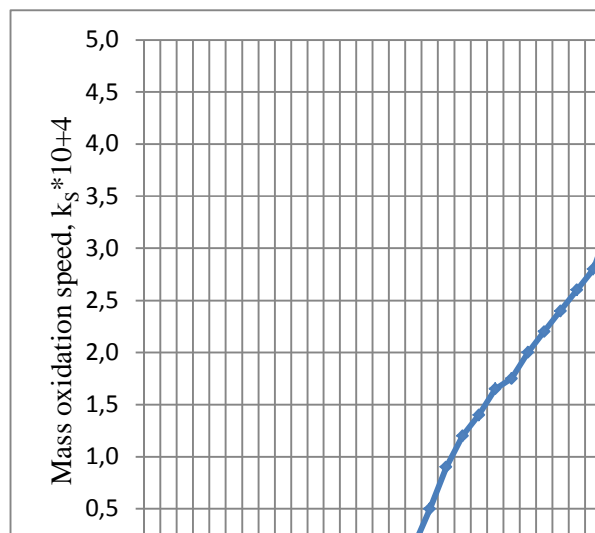
$h_m$  – the value of electrode movement into the furnace during one time step, m;  $\tau_m$  – the time interval between the movements of the electrode into the furnace, c;  $\tau_k$  – time of oxidation of the electrode element at the level of «k», c,  $h$  – the height of the electrode element, m;

In this case, the oxidation speed of the electrode can be calculated by the following formula:

$$k_s = \frac{g_k}{\tau_k} \quad (3)$$

$k_s$  – the oxidation rate of the lateral electrode surface, kg/(m<sup>2</sup>.c).

For each 10 electrodes, the temperature field was calculated [5-7]. A comparison of temperature distribution of the electrode surface ( $t_s$ ) with the oxidation rate allows one to obtain the dependency of the mass speed rate on the temperature of surface electrodes (see Figure 1).



**Figure 1.** Dependence of mass oxidation rate ( $k_s$ , kg/(m<sup>2</sup>.c) on temperature of electrode surface ( $t_s$ , °C).

Comparing data, obtained in accordance with the presented methodology (see Figure 1) at the oxidation rate of carbon materials [3] received in the laboratory, shows that the onset of intensive oxidation of the electrode starts by 500-400 degrees higher than under laboratory conditions and the oxidation rate is substantially below [1], [3]. This is due to the hardening of the working end of the electrode in electric arc combustion conditions.

### 3. Electrode form calculation

The received temperature dependence of the oxidation rate of the electrode lateral surface was used to calculate the form of the working end of a self-baking electrode. The oxidation of the electrode lateral surface is calculated in the following way.

The amount of the oxidation material at each point of the lateral surface of the electrode increased during the moving of the electrode into the furnace. The amount of the oxidation mass can be calculated as follows:

$$G_k = G_{k-1} + k_s F_k \tau_k \quad (4)$$

$G_k$  – amount of the oxidated material of the lateral surface of the electrode «k» element, kg,  $G_{k-1}$  – amount of the oxidated electrode material from the lateral surface of the «k-1» element of the electrode, kg,  $F_k$  – surface of oxidation of «k» element, m<sup>2</sup>.

The obtained dependence, as it was mentioned above, was used in a 3-d mathematical model of thermal work of the self-baking electrode. The model was developed on the basis of the method of basic energy balances [7-9] as follows:

1. The self-baking round electrode was conditionally broken up into elements by height, perimeter and radius.
2. Calculation of the elements temperature is made with the help of numerical methods [7], [8], [9]. When performing the calculation, the values of heat capacity of each of the electrode elements were determined.
3. At each time step of the calculation, the thermal field on the self-baking electrode and its surface temperatures were determined.
4. According to the dependence which is shown in Figure 1, the mass oxidation rate ( $k_s$ ) was determined, and according to equation (4), the amount of material of the working end of the electrode, which is oxidized in each element of the lateral electrode surface was calculated. The amount of the oxidized element material, which oxidizes at the ( $k$ ) level is added to the amount of the material, which oxidizes at the previous ( $k - 1$ ) level.
5. The heat capacity of electrode elements decreases by the value of total heat capacity of their oxidized element parts.
6. If the calculation is not ended, then one must go to item 2.

#### 4. Results

The above-mentioned developments were used in the mathematical model of thermal work of the self-baking electrode.

The estimated form of cracks of the working ends of the electrodes coincides with the form of the working ends of electrodes, which were taken from the ore thermal furnaces after their scabbings (Figure 2).

With the help of the model, the temperature fields and forms of the working ends of electrodes with the diameter of 1,9 m were calculated. The results of the calculations have shown that the working end of the electrode has the shape of a truncated cone, and cracks, formed after melting ribs - a teardrop-shape (Figure 3).

The estimated parameters of the working end of the electrode are close to the actual sizes of the electrode.



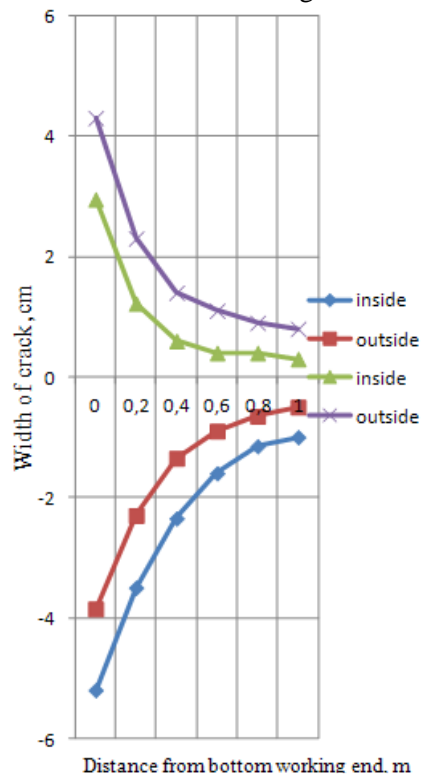
**Figure 2.** Form of cracks in working ends of electrodes

#### 5. Conclusions

The use of calculation of oxidation allows one to reduce the error of calculation of the temperature fields with help of the mathematical model both in the electrode and in the furnace on the whole [10].

Owing to the fact that the form of the working end of the electrode defines the fundamental processes in the electrode and the furnace tub [10], the calculation of the form the working end electrode with different structures of the electrode in various modes of furnace operation, taken with distribution of

thermal, electromagnetic, hydrodynamic fields [11], [12], [13], [14], [15], [16] in the melting bath furnace can allow enhancing the effectiveness of melting alloys in ore-smelting furnaces.



**Figure 3.** Width of cracks in the working end of electrode, calculated using model

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