Analysis of the State of Stress in the Connection of Graphite Electrodes

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Abstract

The paper examines various issues related to the state of stress occurring in the connection of graphite electrodes during their lifetime when operating in electric arc furnaces. It also discusses the impact of graphitization process on the electrode strength. Based on the results of numerical calculations supported by experimental studies, the effect on the connection durability of its design and technological process parameters was determined.

1. Introduction

Conditions that occur during the process of metal melting in electric arc furnaces create the possibility of damage to the electrodes. A common case is breaking of electrode column at the point of connection, the connection being usually obtained by inserting the connector with cut tapered thread into the bottom and top socket of the joined electrodes. The reason for cracking is the drop of mechanical strength in this area of the column and high thermal stress caused by differences in the thermal expansion coefficients of materials used for the electrodes and connectors. Other adverse effects can include a mechanical impact exerted on electrode column by the charge still in solid state (accidental side impact of charge, tilting of the furnace), too large torque when connecting the electrodes, and vibrations occurring during the melting process. Studies of the correct electrode connection design in terms of the best possible selection of thermal and physical properties of materials used for the connector and electrode and of the strength development in this area are possible after calculations performed in order to determine the distribution and magnitude of stresses arising in the joint. Due to the complexity of the problem thus formulated, caused by the anisotropy of materials, the dependence of thermal and mechanical properties on temperature, and the simultaneous occurrence of electric, temperature and stress fields, calculations were performed by FEM using the Abaqus software. The strength of the electrode is also influenced by the graphitization process parameters. During this process, the stress field varying in time may induce cracks on the electrode surface. The paper presents selected issues related to the impact that the graphitization process and design of the electrodes may have on the strength of the connection.

2. Thermal stresses formed during electrode graphitization

One way of graphitization of the electrodes used in electric arc furnaces is the Castner graphitization technique [1]. Graphitization [2], [3] is the process of high-temperature (up to about 2600°C) heat treatment of carbon materials (amorphous carbon), mainly involving a compaction of their structure.

The resulting material is polycrystalline with a degree of graphitization (ordering of the crystal structure) above 60%. In the Castner process, electrodes are placed horizontally in the form of a column to which a constant pressure is applied in order to ensure a good contact between their faces. Thus the column forms a resistor composed of serially connected resistances of the electrodes and transition resistances of the connections through which the current flows (Fig. 1).
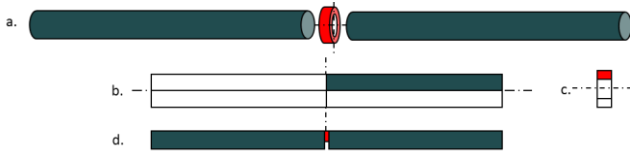

Fig. 1. Geometric model of the graphitized column. a – two adjacent electrodes with a length of 2000 mm and a diameter of 580 mm and an expansion ring placed between them, b – axisymmetric model of single half-electrode, c – model of the ring, d – axisymmetric model of two electrodes in contact with the expansion ring

During the graphitization process, the value of the current varies from a few to tens of amperes by the end of the cycle. The curve of changes in the current rise is determined experimentally and recorded during the graphitization process, making next the basis for numerical analysis [4]. The numerical analysis, in turn, which serves as a reference point for the determination of time-related changes in temperature and stress, allows for modification and correction of the current rise curve. Joule heat that is evolved from the cross-section and external surfaces of the electrode flows into the insulation layer which is formed by coal dust, generating a temperature gradient along the radius (Figure 2). Initially, the temperature rise and its high gradient occur in the electrode contact area, where the resistance to current flow is largest (Figure 2a), after about two hours, the greatest difference is observed between the temperature in the electrode axis and its outer surface (Fig. 2b and 2d). At the end of the process, the temperatures in the electrode cross-section gradually equalize (Fig. 2d). Numerical calculations made after examining several different modes of process operation enabled selecting the optimum method, which allows the graphitization process to be conducted at a reduced energy and with thermal stresses kept at the lowest level possible.
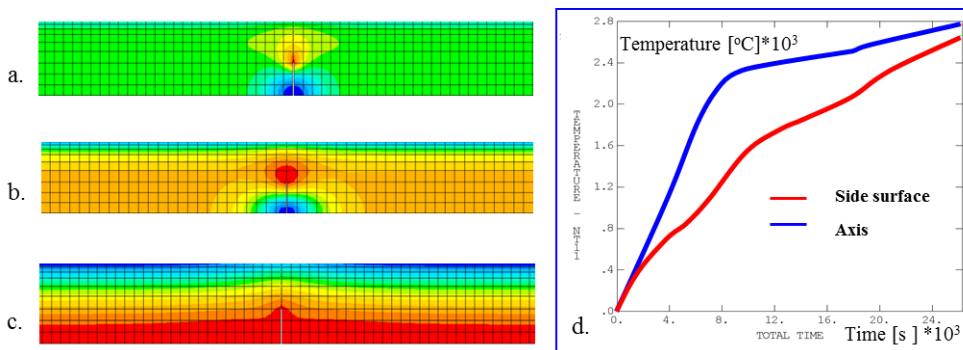

Fig. 2. Numerically calculated temperature changes caused by current flow in the graphitized column of electrodes; a – after 10 minutes, b – after 85 minutes, c – after 420 minutes, d – temperature changes along the axis and on the surface of the electrode within the 7 hours and 30 minutes of process duration

The longitudinal cracks on the side surfaces of electrodes that occur during this process are caused by the tensile hoop stresses, which attain the highest value after the lapse of two hours from the start of the process (Fig. 3).
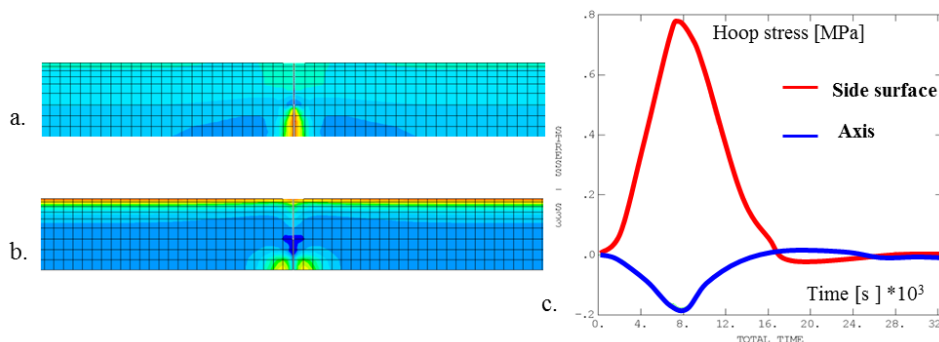

Fig. 3. Numerically calculated changes in hoop stresses during the graphitization process; a – hoop stresses after 15 minutes, b – hoop stresses after 120 minutes, c – changes in hoop stresses along the axis and on the surface of the electrode within the 9 hours of process duration

An important issue is heating of the electrode faces, when they contact each other. The contact resistance is greater than the resistance of the entire electrode, owing to which the tips heat up faster and reach higher temperature than the rest of the column. In the middle part of the electrodes this can result in deformations leading to a deterioration of the contact quality with further intensification of this phenomenon. This is counteracted by constant pressure exerted on columns during graphitization and by the use of ring-shaped spacers made of a material characterized by the flexibility greater than the flexibility of the electrode material. The influence of spacer on local disturbances in the temperature and stress fields is shown in Figures 2a and 3a.

3. Stresses in the area of electrode connection

Under the operating conditions of an electric arc furnace, the column of electrodes is subjected to the effect of torque and bending moments, and further to the effect of weight, thermal stress and vibration. Any changes in the shape and cracks formed during the manufacturing process can contribute to a reduced strength of the column, resulting in the propagation of existing cracks and, eventually, breaking off parts of the electrode. Particularly sensitive is the area where the electrodes are connected to each other and where the largest number of cracks extending through the connector or propagating from the bottom part of the electrode thread socket is observed. Using numerical and photoelastic models, different conditions of the electrode column loading were examined. It was found that in the case of bending of the column (tilting of the furnace, scrap impact), the highest stresses occur in bottom part of the electrode threaded socket below the last turn of the thread (Fig.4) Since the value of stresses which occur in the electrode itself due to the effect of other factors is much lower when the bending moment is operating, it can be assumed that when the crack runs through the electrode, the reason is accidental impact of the scrap.
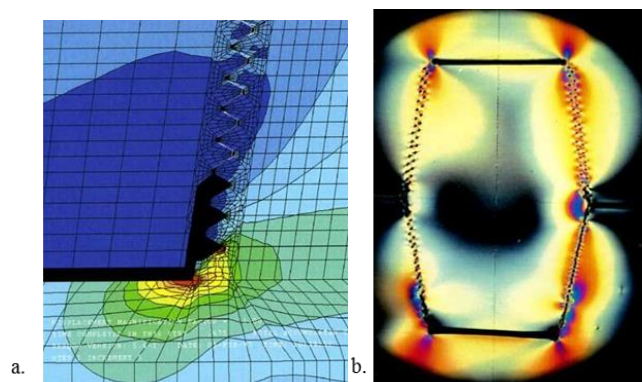

Fig. 4. State of stress in the electrode connector caused by the action of bending moment; a – the result of numerical calculations with a prominent stress concentration in bottom part of the electrode socket, b – elasto-optic model with apparent stress asymmetry along the vertical axis

Increasing the fillet radius between the truncated cone forming a thread in the electrode socket and its bottom may prevent initiation of cracks in this area. On the other hand, the effect of thermal expansion results in "tight" connection between the nut and screw. This can cause significant stress concentration with the results similar to those shown in Figure 5.
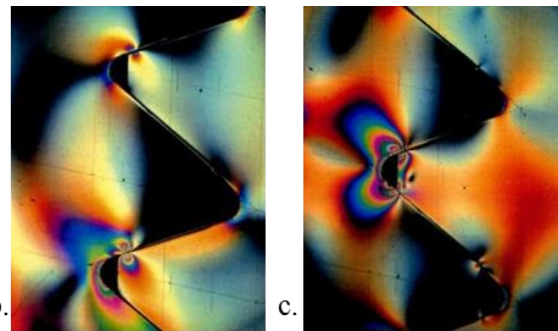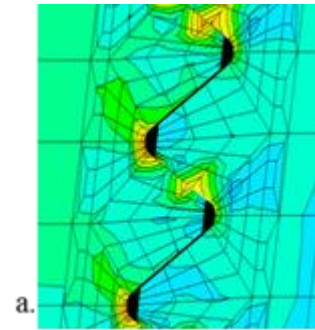

Fig. 5. Stresses observed in the model of threaded connection occurring as a result of the effect of forces caused by differences in the thermal expansion of the connector and electrode, by forces of gravity and incorrectly selected torque moments;
a – numerical model,
b – elasto-optic model showing "loose" connection,
c – elasto-optic model showing "tight" connection

The apex of the tooth opens bottom of the notch and causes multiple increase in the tensile stresses which can result in cracking. Inhibition of thermal expansion in brittle materials is particularly dangerous because of hardly detectable micro-cracks, which join together forming cracks of critical length. The distribution of isochromatic lines similar to that shown in Figure 5c may be due to wrong thread cutting, too large torque, impurities in the connected materials and improperly selected coefficients of thermal expansion of the connector material relative to the electrode. In the case of the occurrence of the above-mentioned deficiencies, in contrast to the effects of bending moment, it is the connector that typically suffers breaking, as confirmed by the results of tests and observations. Choosing the right value of the expansion coefficient for the electrode and the connector was based on the numerical calculations involving different pairs of these values. It was found that the coefficient of thermal expansion of the electrode material should be by one order of magnitude lower than that of the connector.

4. Summary

Operating conditions of graphite electrodes in electric arc furnaces create the risk of their breaking during melting process. An increase in the strength of the electrodes connected into a column by connectors with a tapered thread can be achieved by properly performed operation of graphitization and proper design of the connection. In the case of the graphitization process, particularly important is proper selection of the current curve. As shown by numerical calculations, changes of the current density in graphitized electrodes directly affect changes in the value of stresses in these electrodes. Particularly important are the hoop stresses whose magnitude relative to the instantaneous strength of the material during the heating process approaches the level of actual strength. Based on proper calculations, it is possible to adjust current changes in the Castner furnace so as to minimize the magnitude of stress in the critical time period occurring between the second and the third hour of the process. On the other hand, the diversity of factors causing stress in the electrode connection during operation in an electric arc furnace creates difficulties in the selection of optimum design. Numerical calculations supported by the results of experiments and observations enable re-converting different design variants and finding practical reasons accounting for breaking of the columns and cases when fractures occur in the connectors. Based on these data one can also modify the design details of electrode sockets and connectors. Quite important is also the possibility to select the optimal coefficients of thermal expansion in the electrode/connector pairs in a way such as to minimize the effect of thermal stresses between the thread turns. It should be noted that the numerical models, which served as a basis for the mechanical analysis presented above, take into account the thermal and mechanical properties of graphite materials within the entire temperature range, while the initial and boundary conditions of models have been developed and adopted as a result of long-term cooperation with manufacturers of carbon – graphite products and users of arc furnaces, taking also into account the data given in reference literature [5], [6], [7], [8], [9], [10], [11].

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