THE SØDERBERG ELECTRODE SYSTEM

RECENT RESEARCH AND DEVELOPMENT

NEW CHALLENGES

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SUMMARY

Ever since the Søderberg smelting electrode was invented, an extensive research and development effort has been carried out in our company. The work has been focused on improvements and solving of problems to prevent breakages, the most troublesome event in electrode operation.

Examples of recent activities are: High temperature measurements on electrode materials, viscosity measurements on green paste, temperature recordings and computations on operating electrodes, computer controlled electrode slipping, and a new holder design.

Due to increasing requirements to the electrodes, the possibility of using the Søderberg system in the future is being discussed. Unsolved problems are summarized, and our present work on thermal shock resistance, microcracks, segregated paste, electrode consumption, and electrode tip position, has the purpose to investigate some of them. Our conclusion is that the Søderberg system also in the next decades will maintain its strong position.

INTRODUCTION

The satisfactory operation of a smelting furnace depends on a proper electrode performance. Therefore, ever since the invention of the Søderberg smelting electrode in 1919, an extensive R&D effort has been carried out.

A high current density is normally used in the Søderberg electrodes, generating a great amount of heat within the electrode with subsequent high temperatures. Some energy is necessary for baking of the carbon paste. However, the excess of heat is transported away at the electrode side surface [1].

Current variations, as during furnace shut-downs, are in many cases most dangerous for the operation. Temperature gradients occur, developing high thermal stresses in the baked carbon materials. A good electrode operation can only be obtained if the temperatures are under control. This normally means that a continuous or stable electrode operation must be maintained. In addition to a desired constant current, a controlled electrode slipping and small electrode movements in the furnace should be stressed.

However, from time to time the electrodes are exposed to severe conditions in the furnace. If an electrode is unable to withstand the high currents and temperatures, thermal stresses, irregular slipping, chemical and mechanical wear etc, problems will arise. The most serious one, breakage of the electrode, will affect the whole furnace operation. Our work has therefore been concerned with avoiding/solving problems in connection with electrode breakages.

The present paper comprises mainly the R&D-activities in connection with smelting electrodes carried out by Elkem a/s in Norway. The Elkem Carbon R&D is located near the Fiskaa Carbon plant, a major producer of electrode paste. At the same site, the first Søderberg system was developed. However, work in co-operation with Carboindustrial SA - our associate company in Brazil - is included. As our work in this field covers a wide spectrum, the paper will only contain some examples. Our latest inventions/modifications pertaining to the practical aspects of paste production and control, as well as electrode design and operation, will be of special interest [2].

Changes in the electrode requirements and the possibility of using the Søderberg system in the future, are being discussed. Examples of R&D-activities not yet terminated, or planned further work are shortly presented. References to the various studies are included.

RESEARCH AND DEVELOPMENT

ELECTRODE MATERIALS

General

The electrode paste has been without fundamental changes throughout the years. Of course we have tested, both in the laboratory and in full scale, factors as changes in the grain size and recipe, the degree of material pretreatment/calcination and other operational conditions in the paste plant. Also, various types of carbon raw materials have been tested. These are carefully selected to ensure the best electrode quality, and the manufacturing of the paste is checked through a number of analyses. As previously, however, the Søderberg electrode paste is normally produced from sieved fractions of electrically calcined anthracite, used as the basic dry material, and mixed with coal tar-pitch as the binder.

The carbon materials in question are very complex. At present, we are therefore focusing on a better knowledge of the fundamental composition and structure of the carbon raw materials as well as the green and baked pastes. Material properties at elevated temperatures have also been measured. Information through increased material knowledge, better technology and improved quality is being used to optimize the electrodes at various operational conditions.

Binder

The tar-pitch binder shall make the paste plastic at moderately elevated temperatures in the upper part of an electrode. As the temperatures increase downward, the main part of the volatiles in the binder is expelled and will penetrate down into the hot, baked section of the column. In this area, the carbonized binder will firmly cement the particles of the dry aggregate together.

To specify the binder, our laboratory will measure some parameters. The so-called <u>mesophase</u> content has recently been measured in order to achieve an additional control method. Mesophase is defined as large planar macromolecules that form spherical, anisotropic liquid crystals of the nematic type separating from the otherwise isotropic pitch matrix. The mesophase content is usually estimated by counting such spherical particles, using a polarization microscope.

Until now, the mesophase content has not been included in our binder specifications, but the importance of the phase and its influence on the baking procedure and the structure of the baked carbon is being investigated.

Dry Aggregate

By "dry aggregate" is understood a mixture of two or more fractions of carbonaceous material ready for mixing with the binder. In most cases, the aggregate means calcined anthracite.

During calcination in electrical shaft furnaces there is a wide distribution of heat treatment temperatures in the material, ranging from about 1200 to nearly 3000°C. In this process, some of the anthracite grains will be exposed to temperatures above the graphitization temperature. During smelting operation the electrodes may reach temperatures between 2000 and 3000°C, thus calcination and graphitization reactions proceed in the binder coke and partly in the anthracite aggregate. It is obvious that both each of the grains and the aggregate itself must possess properties in order to fulfil several requirements of the mixed paste when used in the electrodes. One of these is a minimum contribute to the shrinkage during baking and a low thermal expansion at elevated temperatures.

Therefore, dry anthracite grains are being studied [3]. Fig. 1 shows results from extensiometric measurements on single grains of an anthracite filler. The measurements were performed in a graphite resistance furnace at a heating rate of 5°C/min. The thermal expansion measurements of the anthracite grains, heat treated to 2000°C, were parallel to the stratification in the material. Fig.1 shows one type of anthracite. Other raw materials have given different results, which are valuable in quality evaluations. A binder matrix,

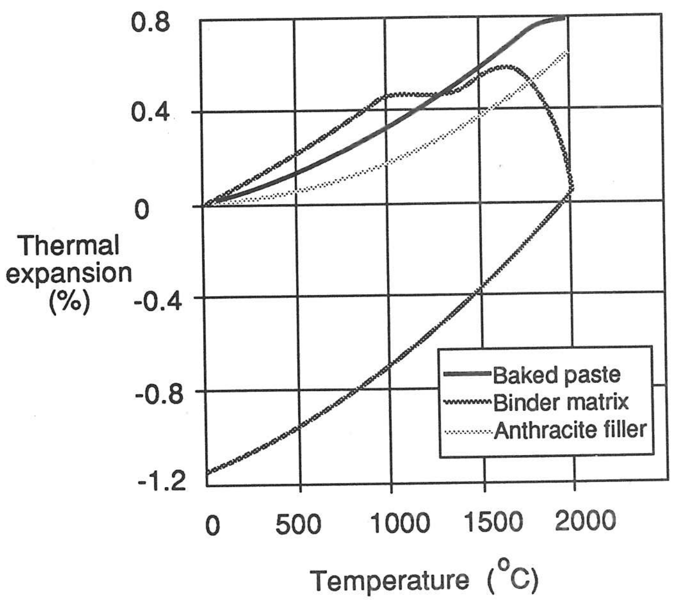

Fig. 1. Thermal Expansion vs. Temperature of Carbon Materials

as well as a baked electrode paste were included in the same test. The thermal expansion of the binder matrix was carried out on baked (1000°C) mixtures of anthracite fines, <100 µm, and tar-pitch. Also the paste sample of the mentioned grains and binder was moulded and baked to a maximum temperature of 1000°C. The shrinkage of the binder matrix was most pronounced, as seen from Fig.1. The effect on the composite electrode material is discussed below.

Baked Paste

Concluding from measurements and calculations, we have found that the tensile strength of a carbon electrode is of fundamental importance in order to resist thermal stresses. Great effort has therefore been made to measure this property up to 2000°C, a critical temperature for the operating electrode regarding hard breakages.

Fig. 2 shows the tensile strength for two different paste samples prepared in the laboratory and baked to a maximum temperature of 1000°C. The diametral compression test was applied, as it provides an experimentally simple method for measuring the tensile strength of brittle materials [4]. The measurements were performed in a graphite resistance furnace fitted to a universal testing machine.The heating rate was 15°C/min, and a 20 min soaking time was applied before testing.

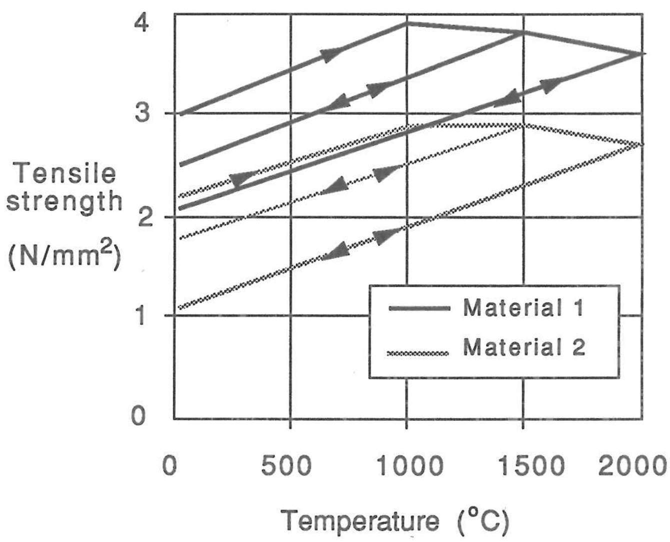

Fig. 2. Tensile Strength vs. Temperature of Two Electrode Materials

As shown in Fig. 2, both the materials have a maximum strength at about 1000°C, the values decreasing towards 2000°C. The diagram also shows the strength variation during cooling and reheating. The following theory can be drawn [3]:
The tensile strength depends on both the test temperature and the maximum heat treatment temperature. Above 1000°C some carbon materials show an irreversible strength reduction, mainly ascribed to crack formation in the polygranular material caused by shrinkage of the binder matrix (Fig.1). Strength variation during cooling and reheating from 1500 and 2000°C, respectively, is reversible and, within certain limits, independent of the cooling rate. It is probably a result of increased internal stresses caused by differences in coefficients of thermal expansion of binder and filler cokes.

The great difference in quality between the two materials can be explained by the origin and heat treatment of the raw materials and the composition of the dry aggregate. Compared to Material 2, the use of Material 1 would be of great advantage regarding strength. On the other hand, a material like this will normally tend to an increase of brittleness, seen from a relatively high modulus of elasticity. This very important strength property may therefore be less favourable. In such a case, additional properties will be collected to acquire a complete picture of the material. (Thermal shock resistance, see later).

We have made an effort to measure most of the material properties at elevated temperatures. Today, it is possible to measure (maximum temperatures given in the parentheses):

- Density
- Electrical conductivity (1000°C)
- Thermal conductivity (1000°C)
- Shrinkage / dilatation (2000°C)
- Tensile strength (2000°C)
- Compressive strength (2000°C)
- Bending strength
- Modulus of elasticity (1000°C)

As already stated, the data are used for selection and control of raw, as well as, baked carbon materials. Another main application, equally important, is as input to mathematical electrode models.

Another project, based on image analysis, also seeks a better knowledge of the structure of baked products, but here in relation to strength. Pastes baked at 1000°C were used for tensile tests at ambient temperatures as described above. As formerly stated, the values decrease with increasing heat treatment temperatures.

Similar sample disks of 10 mm height were prepared as polished blocks for determination of the pore structure parameters. The blocks were examined using reflected light microscopy at low magnification and a Quantimet 800 image analysis system. The measurements made included the number of pores per mm^2 of field analysed, mean pore intercept size, wall intercept size, and the volume porosity. Most of the pore structure parameters varied with heat treatment temperature in a manner which reflected the variations in tensile strength.

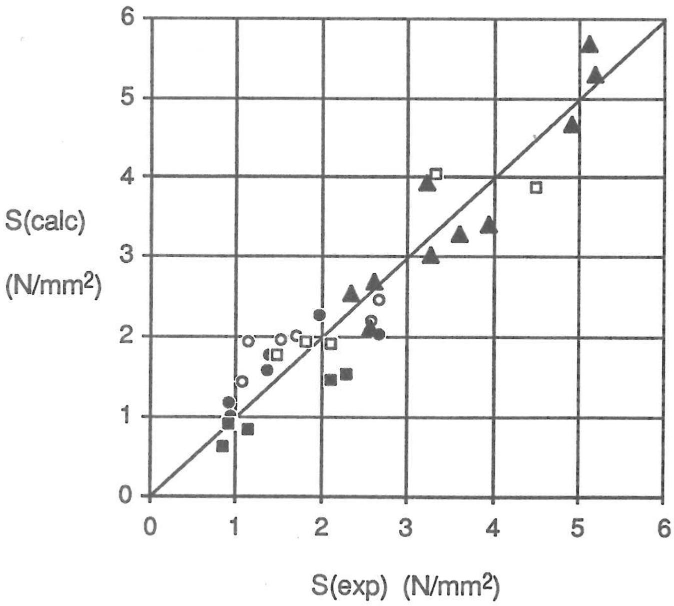

Fig. 3. Comparison of Experimentally Determined and Calculated Tensile Strength

For metallurgical cokes an empirical strength - structure relation of general applicability has been derived. Using this equation, calculated tensile strength, S(calc), were obtained, and a plot of these values against the experimentally determined data, S(exp), is given in Fig.3. The results are from several electrode samples with both electrical and gas calcined anthracites (and graphite) as the dry aggregate [5]. From the plots, it is clear that methods based on image analysis can be used to determine relevant details of the pore structure of baked electrode materials, data which can then be used to predict the tensile strength of the material.

RHEOLOGY OF GREEN PASTE

Viscosity Measurements

After the mixing process, the electrode paste is controlled before shipping. Our plasticity determination is considered to be very important, as it simulates the paste conditions after charging to the top of the electrode.

However, in order to get an even better and, most of all, a more rapid control of the rheological properties of the paste, in particular during the mixing process, a new apparatus was needed. As it was not commercially available, the Elkem Carbon R&D has developed a method [6]. Fig. 4 is a sketch of a parallel plate viscometer for the specific purpose of rapidly measuring absolute viscosities of hot pastes containing particles of sizes up to about 15 mm. The instrument is supervised by an integrated microprocessor that reduces human interaction to a minimum, controls the hydraulically powered plates, and provides evaluated outputs. The measuring range of the instrument covers the wide viscosity range of 10 orders of magnitude.

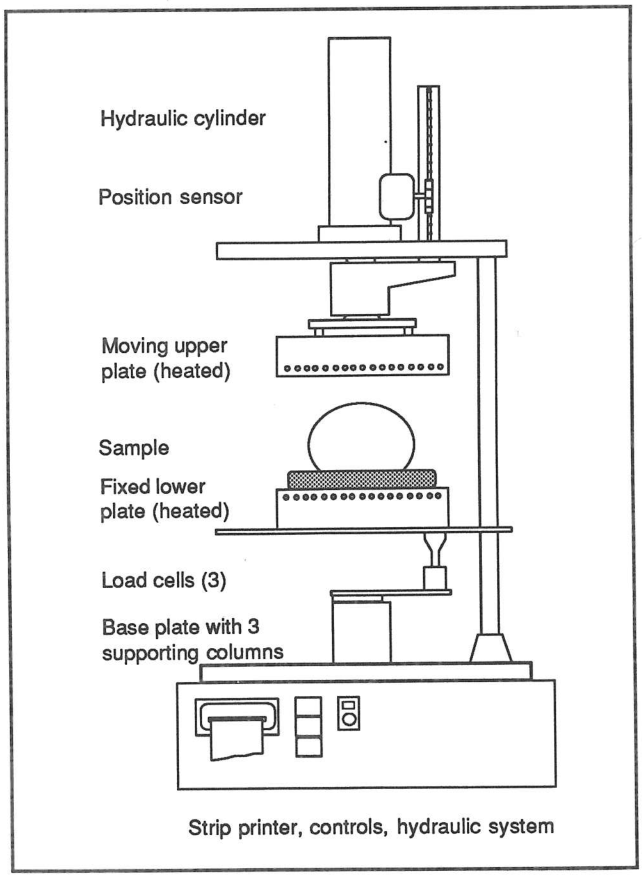

Fig. 4. Parallel Plate Viscometer

While the rheological properties of granulous-viscous pastes cannot be described by a single parameter, this viscometer may provide an absolute reference for quality control of electrode pastes. The method has periodically been used at plants for both electrode and anode paste production. To fully adopt it for regular paste control may take some time. The apparatus is also well suited for laboratory studies.

Paste Softening

After the paste has been charged into the electrode, the softening procedure starts. It is important that the paste flows at a reasonable temperature and fills the casing properly. The softening is normally done by blowing air in behind the suspension mantle, escaping at the clamp level. The air flow and temperature can be regulated. However, to transport the necessary heat to form a fluid paste without segregation - to maintain the paste's consistent mixture of components - is sometimes a problem.

To take better care of these conditions, Elkem has evaluated a system, shown in Fig. 5, different from the conventional method. A hose is lowered into the electrode from the top which is covered by a lid. Air is blown through the hose, according to the need, while the air temperature is regulated by a heating element. By means of this equipment, segregation can be reduced. To handle the equipment is, however, somewhat troublesome. But if real problems occur with paste segregation, or, if the paste level is too low, this is a recommended solution.

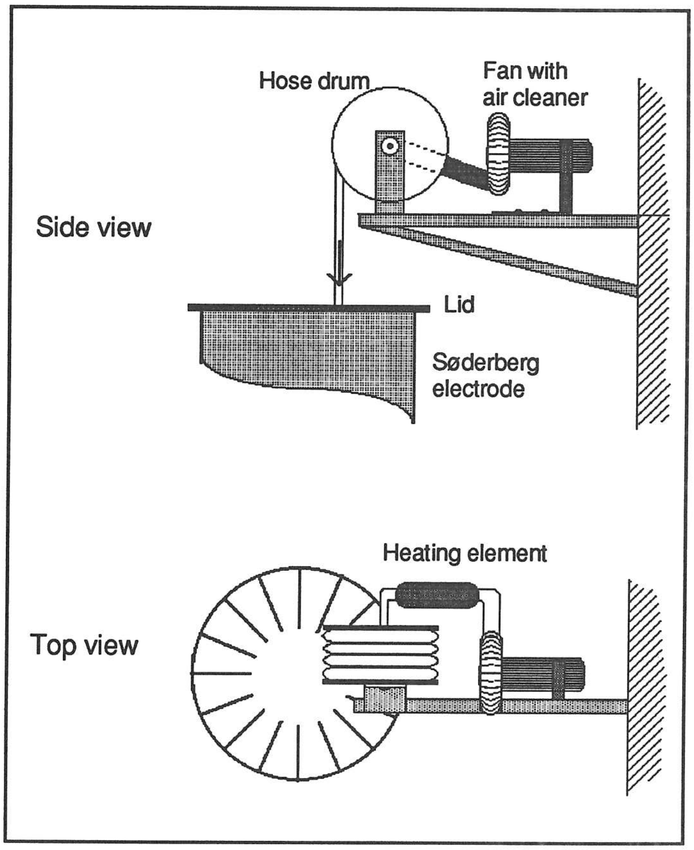

Fig. 5. Equipment for Paste Softening

ELECTRODE OPERATION AND CONTROL

Temperature Measurements

Over the span of many years, basic information about the electrodes has been collected from various types of measurements. The heat conditions are important and much work has been done on temperature measurements. Earlier, the normal procedure was to mount a rig with a number of thermocouples inside the electrode casing, and record the temperatures as the thermocouples were lowered together with the electrode. Now, this rig-equipment has often been replaced by a more rapid and timesaving method, where steel tubes are welded inside the casing. They serve as a protection for the thermocouples, which can be moved in the vertical direction to any desired position. Information is easily collected, but inaccurate measurements may occur. The method is also used, in some electrodes, more or less for a continuous registration of the baking temperatures.

Electrode Models

During the last 20 years, mathematical models and computers have been used to calculate the distribution of electric current, temperatures and thermal stresses in electrodes. All these computations were carried out in two dimensions. The models are valuable tools in the study of electrode parameters, and have been used for a series of furnaces,

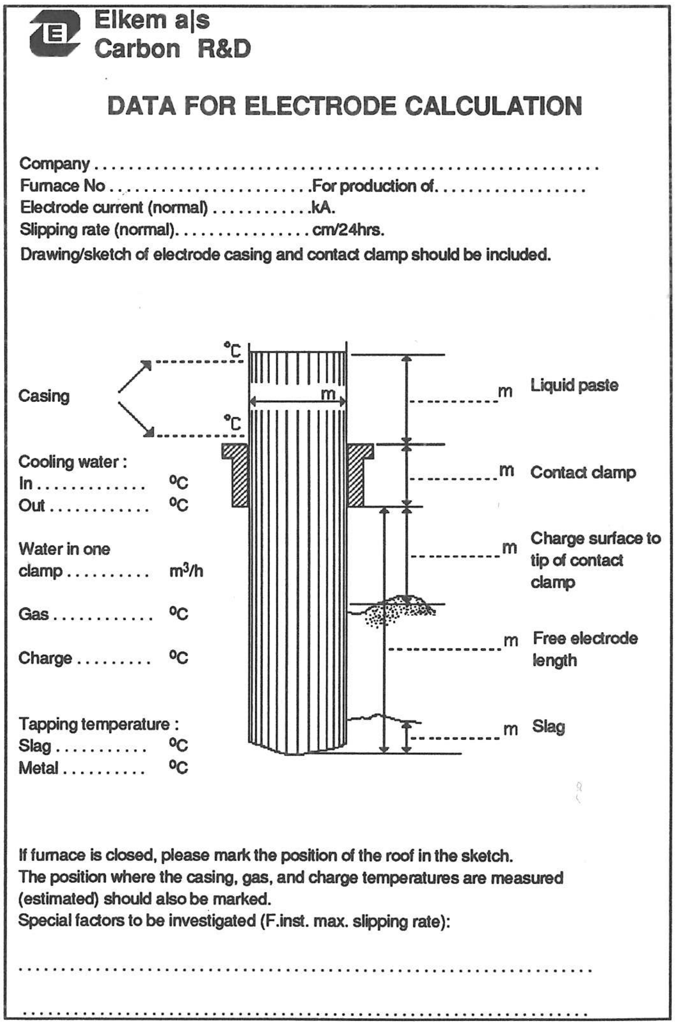

Fig. 6. Input Data for Electrode Models

both in our own company and for customers [7]. The application is relatively cheap and easy. Fig. 6 shows the information necessary to work out the electrode geometry and boundary conditions for a steady state computation in two dimensions. We feel more confident if people following the furnace operation will fill in the sheet. Necessary input for a simulation are also the physical properties for the electrode carbon and casing steel.

As our newest step regarding models, a three-dimensional mathematical program has been developed. [8]. It computes alternating current and temperature distributions in Søderberg electrodes under stationary conditions. The model has mostly been used for the complex electrode holder area, where electrical and thermal asymmetry easily occurs. In several processes the position of the baking zone is critical and computations in three dimension can then be of extreme value in collecting more exact information.

Examples of three-dimensional computations are shown in Fig. 7. Case A shows isotherms in a cross-sectional area of a calculated electrode segment, selected 0.2 m above the lower end of the contact clamps. Furthermore, the segment contains : 1/8 of the electrode cross-section, 1/8 of the steel casing (including two fins with reinforcement), and 2 x 1/2 contact clamps. For the computations, the segment is divided into a total of 2310 gridpoints. Current and heat balances for each of these points are calculated in the case. Case B is another calculation where only one parameter has been changed from Case A: the slipping rate is increased from 0.6 m/24 h to 1.2 m/24 h. The computed results illustrate, as expected, a very low position of the baking zone. The effect of the reinforcement bars as heating elements should be noticed.

Other results with the three-dimensional model on the important holder area show that improvements are possible by establishing an even current supply, a uniform water-cooling and contact pressure for each contact clamp, and better controlled electrode surroundings. The model itself is very complex compared to two-dimensional problems. But most important, the program is a new tool for treating electrodes more correctly and in more detail than before.

Computer Control

Whereas the mathematical models are run on high capacity off-line computers, such as our VAX 11/750, different type of computers are used for data logging and process control on-line to the furnace.

Such process control computers have become increasingly important for supervision and control of the whole furnace operation, of which the Søderberg electrode system constitutes a significant part. Thus, the computer is useful for collection, supervision and reporting of all relevant data for the electrode operation which can be measured. And the on-line computer is an efficient tool to estimate variables which cannot be measured directly on a continuous basis, such as the free electrode length. Also, the computer keeps track of the long-term electrode usage, and calculates the "best possible" value for the specific consumption factor (mm/MWh). This factor is one of the parameters used for computer controlled slipping.

The purpose of the computer controlled electrode slipping, developed by our company , can be summarized as follows:

- To compensate electrode consumption and stabilize the holder position and the electrode length
- To ensure proper baking of the electrode
- To monitor electrode slipping and to sound alarm for electrode slip-through if necessary

The principle for the slip control is shown in Fig. 8. The control routine performs electrode slipping at regular intervals to compensate electrode consumption. The slip length is measured after each slip by special measuring equipment. Based on specific electrode consumption, electrode power, electrode current, and a baking factor, the control algorithm calculates electrode consumption and the amount of baked electrode since the last slip. The specific electrode consumption can either be specified by the operator or calculated by the computer.

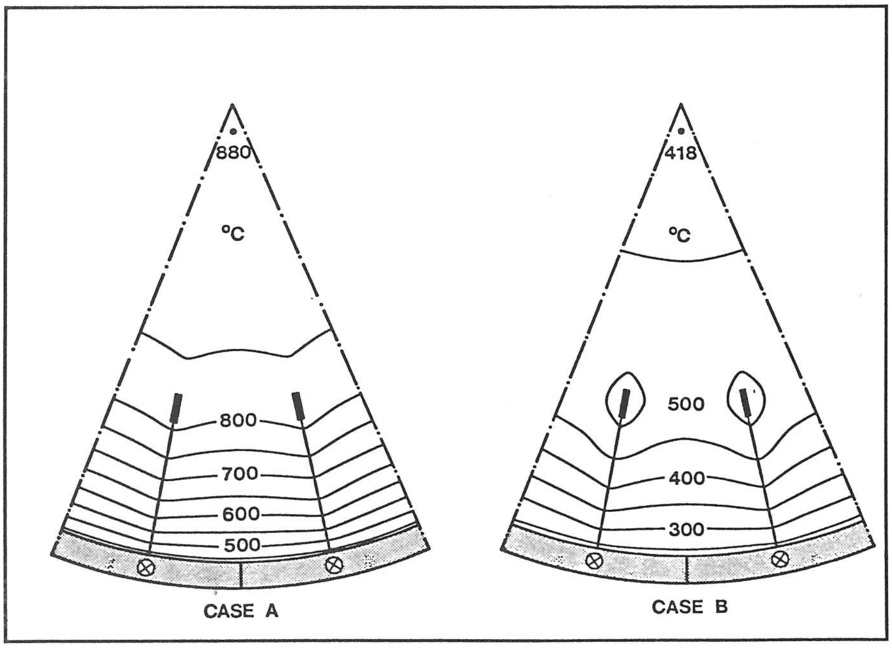

Fig. 7. Three-Dimensional Computations of Isotherms in Cross-Sections of Electrode Holder

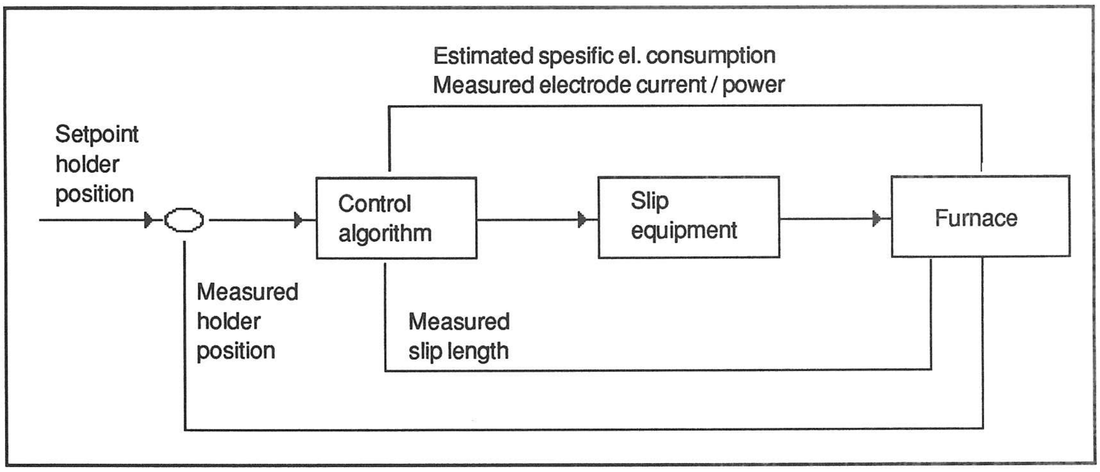

Fig. 8. Electrode Slip Control. Principle Diagram

When electrode consumption since the last slip is equal to the last slip length, a new slip is initiated. However, to ensure proper baking of the electrode, a new slip is not initiated before the amount of baked electrode since the last slip is equal to or greater than the last slip length.

However, it is not possible to estimate the electrode consumption accurately enough to avoid changes in the electrode length. Therefore a feedback is taken from the holder position to stabilize the electrode length. The slip interval is increased when the holder moves upwards and is decreased when the holder moves downwards [9].

NEW HOLDER DESIGN

Since the original development of the Søderberg electrode, no fundamental change in design has taken place. Some improvements have, however, been made on the electrode equipment to maintain a good control of the operation. One of them is the Elkem Modular Electrode Holder, developed by Elkem Technology in co-operation with the R&D Center [10].

The experimental part of the project started on a small scale in 1980 on an electrode 500 mm in diameter. After several test installations, the system is now in use on one furnace for the production of ferrosilicon (Elkem's Bremanger Smelteverk, Norway; electrode diameter 1120 mm.) and two furnaces for manganese alloys (BHP's TEMCO, Australia; diameter 1400 mm). Regarding future installations, nine furnaces at seven different plants in China and two in Czechoslovakia with electrode diameter 1250 mm, and one furnace in Venezuela with electrode diameter 1600 mm are on order. Installation of the first furnace in China will start early 1989.

The principle of the system is shown in the sketch in Fig.9. The contact clamps and the pressure ring are combined to form one unit. As seen from the cross-sectional plan, Fig. 9, the fins are extended through the cylindrical steel casing into the contact assembly. The contact unit is a spring-loaded device which conducts the current to the fins of the electrode casing. The number of fins will depend on the number of contact units required, and this in turn depends on the electrode diameter and the maximum current. Suffice is to mention that the slipping unit is hydraulically operated and the forces are also here applied to the extended fins.

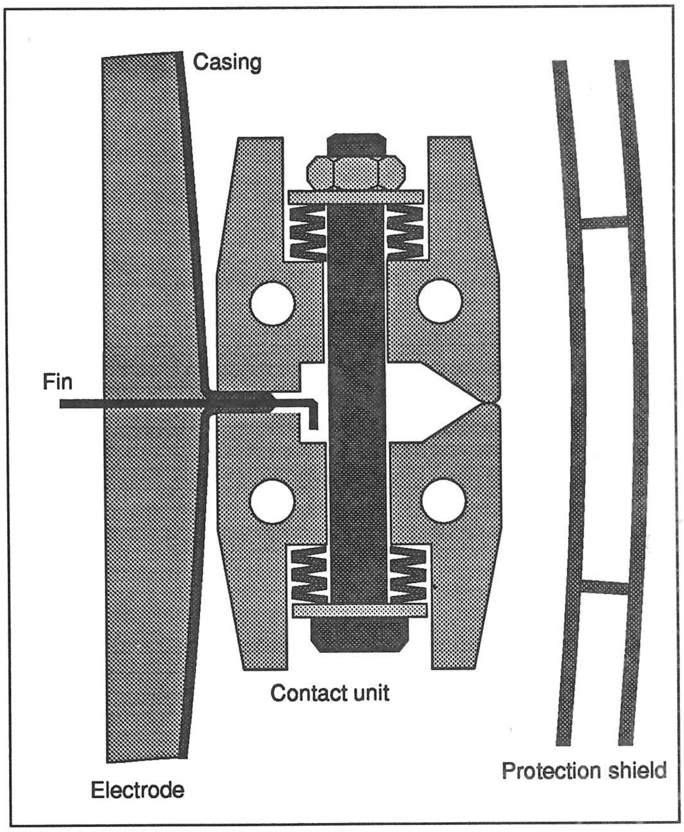

Fig. 9. Modular Electrode Holder

Some of the main features with the modular holder are:

- Standard contact and slipping units for all electrode diameters
- Simplicity in design, manufacture and operation
- Reduced downtime for maintenance
- A drastic reduction in spares inventory

To investigate possible improvements of the new system, measurements and model computations have been carried out [11]. So far, studies of operating electrodes have given the following conclusions:

- The electrode performance is good with normal current and high, as well as low, slipping rates.
- A somewhat higher position of the baking zone than in conventional holders is obtained.
- The heat loss to cooling water is reduced.
- The maximum current through one contact unit is 10 kA, although 14 kA was used during a test run in our pilot plant, without any ill effects.
- The slipping rate of the electrode may be increased considerably compared to a conventional electrode holder.

NEW CHALLENGES

STATUS

Operation and Technology

The main goal with all the work on Søderberg electrodes is to prevent electrode breakage and to decrease the electrode carbon consumption to a minimum. Both factors have a considerable effect on the operational costs. Electrode breakage should normally be avoided by using proper equipment and electrode materials under favourable operating conditions. The electrode consumption is normally a more complex problem, as discussed later. At present, the following conditions can be summerized:

- Soft paste breakages are the most serious type of electrode problems. Such breakages will seldom occur. However, should they do so, the cause can in most cases be given. The problems can be prevented by using existing knowledge about the relation between slipping rate and electrode current/heat generation, i. e. the main parameters for determining the position of the baking zone. Also the slipping increments, electrode casing design and welding, heat conditions of the surroundings, as well as the softening of electrode paste, should be taken into account. The various effects can easily be simulated by mathematical models and, if needed, verified by temperature measurements.The use of on-line computers to control the slipping has been a great improvement.

- Hard breakages are the most common electrode problem in many furnaces. During shut-downs or other unstable operation, abrupt temperature changes will occur. The electrode materials are exposed to high thermal stresses, and failures may occur. Based on a series of simulations with our electrode models, recommended shut-down procedures for electrode operation have been worked out. A good quality control of the electrode materials, especially at elevated temperatures, is important.

From electrode measurements and calculations, as well as practical experience at the production plants, much knowledge has been collected. The results have revealed that it is possible to come closer to the optimum conditions for an electrode system. General recommendations have been worked out. But each furnace or even each elctrode needs to be treated individually in order to obtain the best results. In many cases, one out of three electrodes breaks, even if the conditions are nearly the same. Therefore, very small improvements may be necessary to save all three.

Alternative Systems

The selection of electrodes for a specific process and for each furnace will be based on technical and economical factors as: dimensions, current capacity, consumption, pollution, operational safety, and costs. The Søderberg self-baking electrodes have the main advantage to cost much less than the alternative prebaked electrodes. Even if the latter can carry a somewhat higher current density, Søderberg electrodes are mostly preferred. In addition, in large furnaces, the Søderberg system is always used , because the size limit for the prebaking technique is a diameter of about 1.5 m. Søderberg electrodes are also operated where a small amount of iron introduced with the casing can be tolerated in the product.

In the production of silicon metal, normally using prebaked electrodes, modified Søderberg electrodes have been tried. One method is to reduce the iron by selecting special types of furnace raw materials combined with a paste low in ash and a very thin steel casing, or the steel replaced by other metals or alloys. In patent literature, several other modifications can be found. Some of them have been tried in industrial scale. However, a proper electrode operation seems difficult to obtain, and still the prebaked electrode is dominating in the silicon process.

At present with the existing furnace technology, there seems to be no alternative electrode system to the Søderberg principle. This is especially the case for ferroalloys, pig iron, and calcium carbide, where the Søderberg electrodes are expected to be used for many years. On the other hand, also the Søderberg system must be improved and further developed. More instrumentation and hollow electrodes for multiple applications are two factors to be mentioned.

FURTHER WORK

Future Trends

There is a certain trend toward the use of larger ferro-alloy furnaces and electrodes. Even if the increase in furnace sizes during the next decades will slow down compared to in the past, electrode diameters of 2 meters will probably be normal with current load exceeding 150 kA. In some cases, it seems that a satisfactory electrode operation is the main limit for the furnace size.

To optimize the furnace production, the maximum electrode load is desireable and often applied. In many cases, it is difficult to accept limits in the electrode itself and in the equipment, the results being electrode breakage with high costs.

A smooth operation of the electrodes is of growing importance, as the consequences of malfunction increase with the furnace size. In the future there will be a demand for not only larger electrodes with increased current load, but electrodes tolerating high carbon consumption, resisting thermal shocks and chemical attacks, causing negligible pollution, etc. These factors will impose stricter specifications on the Søderberg electrode system, which means that both theoretical and practical work within this field will continue.

From the technical status, we have seen that a proper electrode operation should be possible. However, electrode problems may unfortunately occur even if the best-known equipment, paste, and operation are used. The reasons may be uncontrolled conditions or malfunctions regarding the following:

- Segregated paste
- Bad welding or collapsing of the casing
- Sudden current supply cut-off
- Sliding of the whole electrode
- Long electrode slipping after breakage or connected to a too high consumption
- Forced electrode slipping connected to high consumption
- Asymmetric holder temperatures and current distribution
- Local cooling due to water leakages
- Local hot zones due to gas blows from the furnace mix

As reported, some of these problems have been investigated, and new methods for solving them are being considered.

Examples of Desired Improvements / Unsolved Problems

The continuous electrode operation should be aimed at. Examples are: Charging of paste should be done every day, the fins in the casing sections should be welded in the joints (without fin overlapping), and the slipping of electrodes should be carried out in very small increments (preferably continuous).

Other factors affecting an even electrode operation are depending on the design and the construction of the electrode itself, as well as the electrode installation/position in the furnace pot. Axisymmetric conditions regarding current and temperatures are difficult to obtain due to:

- The electrical connections from transformers to holders
- The complex electrode holder
- The adjacent electrodes
- The proximity effect

A continuous (and axisymmetric) system will also be strongly reflected in the following items.

The electrode current must be within recommended ranges in order to secure a safe operation. Nevertheless, electrodes may even be operated far above this range. During continuous operation - steady state - such high load will normally not cause any problems, but during shut-down thermal stresses will occur. Many of the hard breakages are related to a very hot electrode. Therefore, by using a high current load, it is recommended that the current should be reduced 10 to 20 percent during a period of 1 to 2 days before a planned, long shut-down. In this way, it is possible to produce a new and colder electrode before the current is switched off. To develop electrode materials with higher resistance towards operational changes is another important factor.

The electrode consumption is reflected by the slipping rate. It varies considerably from one process to another, and even for the same product. Numbers from about 10 to 130 kg paste/ton metal are reported. Therefore, the consumption has a significant effect on the process economy [12].

In some cases, the linear electrode consumption exceeds the safe slipping rate. At intervals, a reduction of the current has to be made to increase the electrode length. Both by "forced slipping" and "long slipping" the reduced load during the process for baking-in of new electrodes represents a considerable production loss. The quality of such a new electrode is normally poor due to the discontinuous process. To overcome these problems will be of great value.

Some factors affecting the electrode consumptions are:

- Carbon stoichiometry
- Electrode current / Operating resistance
- Electrode tip position
- Size of smelting crater / Gas flow rate
- Accumulated slag in furnace
- Moisture content in raw materials / Water leakages
- Product - Temperatures / Corrosive gases
- Carbon paste quality / Paste segregation
- Uneven baking process

Of these items, we have, for the same process, only seen a clear relation between the carbon stoichiometry and the consumption. If there is a stoichiometric lack of reducing agents in the charging materials to the furnace, more electrode carbon will be consumed.

In addition to the normal quality control, we are examining the reactivity of the electrode materials in furnace gas atmospheres. A method to measure the resistance towards thermal shocks of carbon materials is also being developed [13], based on a Japanese work.

Thermal shock resistance, R, is a property for high-temperature materials defined as

$$R = \frac{\text{thermal conductivity} \cdot \text{strength}}{\text{thermal expansion} \cdot \text{elasticity}}$$

Fig 10 shows a simplified sketch of the apparatus. During the test, a circular disk - 80 mm in diameter and 10 mm high - is compressed axially between two graphite electrodes. The disk is heated rapidly in the central area by

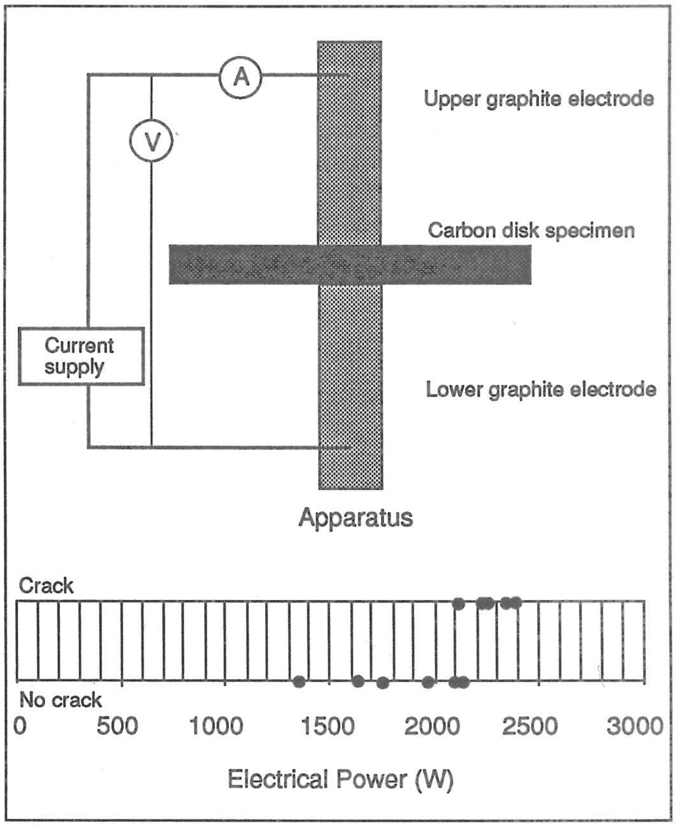

Fig. 10. Test Apparatus for Thermal Shock Resistance

conducting electric current through the material for a fixed time. A possible crack formation in the periphery of the specimen is detected by using a piezoelectric element with amplifier. This is necessary, because possible cracks at the test temperature may be closed and difficult to see after cooling to room temperature. If no cracks are found in the material, a new disk of the same material is heated by use of a higher current. This procedure is repeated totally 10 to 20 times, before the limit effect for the crack formation is determined.

The limit of fracture is illustrated in the lower part of Fig. 10, showing the test of an anthracite based electrode sample. The basis for the investigation is that the electrical effect in the disk at the test conditions shall be proportional to the shock resistance. Therefore, the electrical power in the figure is given together with the results: "No crack" or "Crack".

The test results from the method show a saticfactory relation to calculated shock resistance from material properties put into the theoretical formula. However, the apparatus will be further improved, in order to increase the test accuracy.

The work on electrode consumption will continue with studies of the mechanisms (tip consumption, surface losses, breakages), as well as of methods to reduce or control the consumption. Experience from graphite electrodes in electric arc furnaces for steelmaking will be used, since very little work is done regarding the Søderberg electrodes.

Electrode materials will always have a central position in our work. As an electrode paste producer, Elkem Carbon will continue with improvements of the paste. In the following two examples are presented, regarding paste segregation and structures.

Segregation can occur in a Søderberg electrode. Above the contact clamps we will then observe segregated paste with almost no coarse particles along the outer casing, and unsegregated paste (normal composition) in the centre. See Fig. 11.

We decided to increase our knowledge of the basic mechanisms for Søderberg paste flow pattern and segregation. The problem has been discussed at meetings in mathematical study groups concerning industry problems, arranged by the University of Oxford.

The discussions concluded that segregation is most likely caused by a differential flow between coarse particles and a binder-plus-fines sludge. It was further noticed that the viscosity of segregated paste is some order of magnitude lower than the viscosity for normal paste, implying that the flow patterns for the normal paste core can be computed without considering the flow within the segregated region.

An approximation for the flow within the unsegregated paste has been developed assuming a long, thin core, linear increasing temperature (downward), and neglecting influence of the casing [14]. The model predicts flow pattern as indicated in Fig. 11, including an approximation for the area where the core reaches the casing.

So far, the model gives a basic understanding of the flow pattern. Further development is, however, necessary in order to supply an engineering tool for studying how to influence the shape of the unsegregated paste core, especially determining the area where the core reaches the casing. We are planning to establish a numerical model to simulate the patterns for arbitrary (cylinder symmetrical) temperature distributions (necessary as the paste viscosity is extremely temperature dependent), including flow details near the casing. Such a model will further improve our ability for solving electrode problems related to paste segregation.

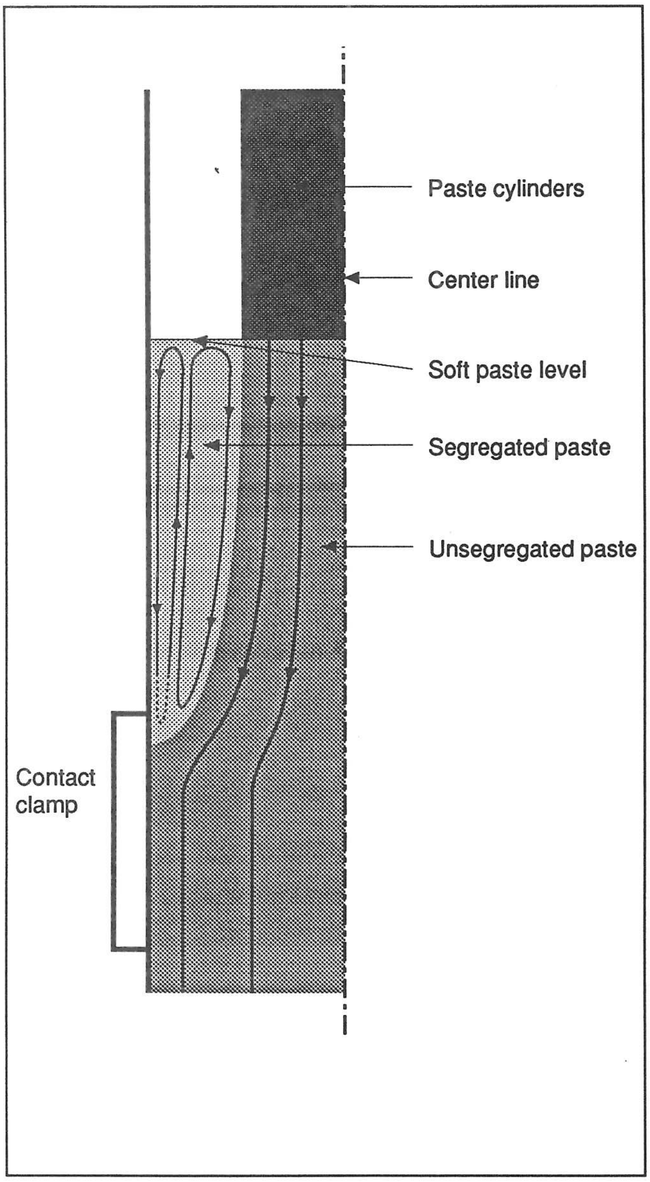

Fig. 11. Possible Flow Patterns in Segregated and Unsegregated Paste in a Søderberg Electrode. (Flow in unsegregated paste predicted by analytical model.)

Structures of the baked carbon materials and how they are influenced by the raw materials, is another research project. Mathematical models, based on finite element analysis, have been used to simulate variations in the material properties. Thermal expansion of the anthracite grains and shrinkage/expansion of the binder matrix - shown in Fig.1 - as well as the modulus of elasticity, are most important. The temperature dependence is included.

In our introductory studies thermal stresses for three different carbon materials - i. e. three models - have been computed [15]:

- Material without cracks
- Material with cracks in the binder matrix
- Material with cracks at the grain surface

Examples of the two first mentioned models are presented in Fig. 12. Thermal stresses are developed at 2000°C due to the unequal thermal expansion of grain and binder coke, or to shrinkage or puffing in any of the different phases. During baking, the binder coke will tend to shrink, while the filler grains are thermally stable at these temperatures. This difference in physical behaviour will develop thermal stresses in the material; mainly compressive stresses in the grains and tensile stresses in the binder coke.

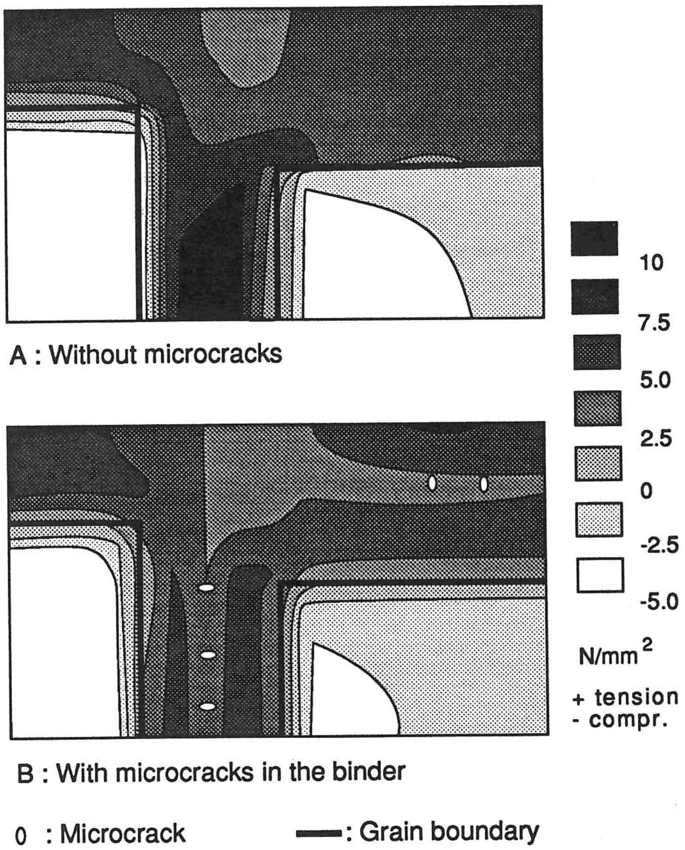

Fig. 12. Finite Element Analysis of Thermal Stresses in a Polygranular Material

The models show that the stresses are too high for the material and therefore there has to be a mechanism for relaxation of the stresses. Formation of pores and cracks will partly reduce the stresses. It has been found that formation of small cracks, situated in the binder coke, will give a considerable relaxation, while cracks at the grain boundaries will only have a minor effect.

The calculations show changes of the stresses during repeated heating and cooling which agree well with laboratory tests of the temperature dependent strength of the material. Going into detail about theories and results is not possible in this connection. The project will continue.

Maintenance work on the electrode equipment is very important. Could the furnace shut-downs be kept shorter than 3 to 4 hours, electrode cooling would be reduced and breakages nearly avoided. On the other hand, a prolonged stop period gives an unfavourable increase in thermal stresses. Planned shut-downs with predetermined procedures are the best. This is not always possible, but alternative operational solutions should be worked out.

By an increase of the electrode current (and surrounding temperatures) during normal operation, the load on electrode equipment, such as bus tubes and holder components, will be higher. There will be an increasing tendency for critical shut-downs, in many cases combined with water leakages. Maintenance is important in order to prevent such leakages causing rapid cooling of local parts of the electrode, developing high thermal stresses.

Maintenance also focuses on the equipment itself. Good design, high quality materials and new and better constructions must be aimed at. To design a holder with an equal distribution of the current for each contact unit may improve considerably the axisymmetric conditions. An optimal casing design with improved welding technique is another example.

The electrode tip should be in its correct position in the reaction zone. To maintain a proper control of the electrode, as well as the furnace conditions, the furnace operator needs to know the position of the electrode tip. Therefore, a large number of methods have been suggested over the years. They can be divided into four categories (In the parentheses methods tested by Elkem are given):

- Equipment outside the electrode (Electrode weighing and Gas temperature measurements)
- Equipment inside the electrode
- Equipment through a hole in the electrode (Mechanical sounding and Doppler radar)
- Method for direct manual sounding (Steel rod)

The last one is well-known and probably the mostly used method. A steel rod is pushed through the furnace charge from the edge of the furnace pot. The electrode tip is reached with the rod and the length can be measured / calculated. Improvements of the method are being investigated and further changes will be made. The disadvantage is that the furnace has to be shut-down, so an ideal method to give a continuous and real measurement of the electrode tip is still missing.

The electrode length can now be estimated by process computers. As seen, an on-line computer gets accurate measurements of the holder position and the slipping and calculates the electrode consumption. In addition, an initial value of the electrode length is obtained with a manual sounding technique. Based on this information, the electrode length calculation is continuously updated by the computer as a function of time. After some days, the manual sounding must be repeated for correction of the length, and then the computer again takes over. Experience has shown that the time periods between these furnace stops and manual measurements can be increased considerably.

Additional indications of the electrode length, such as gas temperatures close to the electrode and furnace gas analyses, can be combined with the mentioned method. This can result in very good estimates in closed furnaces. However, the work regarding tip position has to continue, both in view of metallurgical aspects, and for safety reasons.

Instrument and computer applications are main tasks for the future. Today the important parameters, current and slipping rate, are carefully followed by instruments, together with the holder position. Other measurements are rather few, but the position of the baking zone and the level of soft paste can be measured. The current supply to each contact clamp, cooling water flow and temperatures in the clamps, air flow and temperatures in the suspension mantle, and some other parameters can also be recorded. However, since the operation of the Søderberg system is mainly a question of temperature control, additional thermocouples should be mounted.

As already mentioned, computers are used for several purposes in connection with electrode operation :

- Electrode slipping control
- Electrode length estimation

Computer control of other electrode functions is possible:

- Current supply during furnace start-ups and shut-downs
- Current supply in connection with forced and long slipping
- Current for baking-in of complete new electrodes
- Collecting data from various instruments

CONCLUDING REMARKS

The electrodes are the most vital part of the furnace and cannot be separated from the rest of the process. We would like to make the following statement :

- A good furnace operation means a good electrode performance - and vice versa.

On the other hand, fluctuations in the furnace parameters with an irregular operation will normally result in unfavourable electrode conditions. To maintain satisfactory electrode operation is impossible.

Extended use of instruments and computers is one step to connect the various furnace systems. Another main task for the future is to develop mathematical models for the whole furnace and not only for separate parts, as at present exist for electrodes, linings, chemical reactions, electrical systems, etc.

Already today, people working with the electrodes are not only paste specialists, equipment designers, and furnace operators. They might as well be experts within instrumentation, computer control, and mathematics. Could all these R&D-activities effectively be combined with industrial experience, the integrated furnace system would obtain the best results. Also the electrodes will be improved, and the Søderberg system may live for another 70 years.

REFERENCES

1. R. Innvær, K. Fidje, and R. Ugland, "Effect of Current Variations on Material Properties and Thermal Stresses in Søderberg Electrodes", INFACON, Rio de Janeiro, 1986

2. R. Innvær, "Recent Research and Development connected to the Søderberg Electrode System", VIII Seminar on Electric Furnaces/Second Iron Alloys Seminar, Sao Paulo, 1987

3. B. Larsen, M. Sørlie, and R. Ugland, "High Temperature Properties of Anthracite Based Electrodes", Carbon 86, Baden-Baden, 1986

4. A. Rudnic, A.R. Hunter, and F.C. Holden, Materials Research & Standards (1963) 283

5. J.W. Patrick, M. Sørlie, and A. Walker, "Strength-Structure Relationships in Baked Carbon Materials", Carbon 88, Newcastle-upon-Tyne, 1988

6. K. Tørklep, "Viscometry in Paste Production", AIME 117, Phoenix, 1988

7. R. Innvær, L. Olsen, and A. Vatland, "Operational Parameters for Søderberg Electrodes from Calculations, Measurements, and Plant Experience", Mintek 50, Johannesburg, 1984

8. R. Innvær, K. Fidje, and T. Sira, "Three Dimensional Calculations on Smelting Electrodes", Electric Furnace Conference, Atlanta, 1985

9. A. Holmelid, A. Hempel, and P. Kristiansen, "An Integrated Process Control and Information System for Better Process Operation and Product Information in the Ferroalloy Industry", Electric Furnace Conference, Dallas, 1986

10. G. Ellefsen and K. Evensen, "Elkem Modular Electrode Holder", Electric Furnace Conference, Kansas City, 1982

11. A. Vatland, K. Fidje, and R. Innvær, "Data Registration and Calculations on Søderberg Electrodes with Modular Holders", Electric Furnace Conference, Chicago, 1987

12. J. Westly, "Electrode Consumption in Production of 75 % FeSi and Si-Met.", Electric Furnace Conference, Toronto, 1984

13. B. Larsen, Internal Elkem R&D-Report, 1988

14. T. Bergstrøm, S. Cowley, A.C. Fowler, and P.E. Seward, "Segregation of Carbon Paste in a Smelting Electrode", submitted for publication 1988 in IMA J.Appl. Math.

15. B. Larsen, Internal Elkem R&D - Report, 1986