

**MINIMIZING THERMAL STRESS DURING SHUTDOWN  
OF SØDERBERG ELECTRODES**<sup>1</sup>B. Larsen, <sup>2</sup>H. Feldborg, <sup>3</sup>S.A. Halvorsen<sup>1</sup>Elkem Carbon AS, Vaagsbygd, N-4675 Kristiansand S, Norway; bjornar.larsen@elkem.no<sup>2</sup>Elkem Carbon AS, Vaagsbygd, N-4675 Kristiansand S, Norway; heidi.feldborg@elkem.no<sup>3</sup>Teknova AS, Gimlemoen 19, N-4630, Kristiansand S, Norway; sah@teknova.no**ABSTRACT**

*Submerged arc furnaces (SAF) for production of various ferroalloys, platinum, nickel- or copper matte are most often equipped with Søderberg electrodes. For a well operated furnace, the risk of having an electrode breakage during normal load is quite small. But all furnaces need shutdowns for planned maintenance, and some furnaces are regularly stopped for cost saving reasons during energy peak hours. Such dynamic temperature conditions will provoke thermal stresses in the electrodes, and it is important that the electrodes can withstand these stresses without breaking. The worst case is an operating accident or unplanned shutdown; conditions that can result in severe thermal stresses and increased risk for electrode breakage.*

*It is, to some extent, possible to influence the level of stresses during a shutdown and hence it is also possible to reduce the risk of having an electrode breakage. Elkem Carbon has for many years used mathematical models, ElkemD and ElkemT, for temperature and stress analysis during shutdowns. These tools make it possible to understand the mechanism of stress formations and to give recommendations on how to handle furnace stoppages in the best possible way. Using optimized shutdown procedures will give less down time due to breakages, and hence a more efficient furnace operation. The duration of a shutdown determines the stress levels. An optimized shutdown procedure therefore depends on the shutdown duration. Short shutdowns should be recovered fast, while longer shutdowns need longer recovery times.*

*This paper discusses how the stresses are influenced by various parameters such as electrode size and current, "powering down" practice, shutdown duration and recovery times. Maximum stress versus shutdown duration and recovery time are presented in informative diagrams making it easier to understand how various shutdowns should be handled.*

**KEYWORDS:** Søderberg electrodes, mathematical modeling, thermal stresses.

**1. INTRODUCTION**

The Søderberg electrode was invented approximately 95 years ago. This new technology with self-baking electrodes made it possible to make "huge" electrodes up to 850 mm in diameter. Before this, the largest electrodes had been of prebaked type with diameters up to 650 mm.

Over the years the Søderberg technology has evolved, and we now see electrodes with more than 2 meters in diameter and transformer capacities up to 120 MVA.

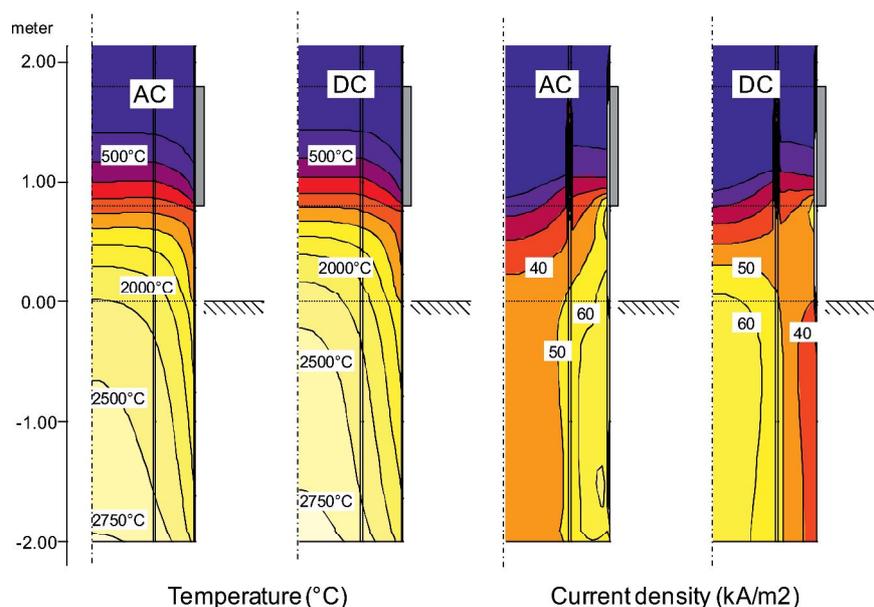
With increasing diameter and increasing load, the operation of the Søderberg electrodes has become more demanding; for the equipment, for the handling procedures and also for the electrode paste. In the first, smaller Søderberg electrodes, the clamps were often more open and gave a safer position of the baking zone. Today's contact clamps are generally much better cooled. This is beneficial for maintenance, but brings on higher risk due to lower and more critical position of the baking zone.

Hard breakages were more frequent in the old days, in part because the understanding of important parameters of the electrode paste quality was less developed. Equally important is the

understanding of stress formation in the electrode paste, which has considerably improved since then [1, 2].

Elkem was probably the first company to use mathematical tools to improve electrode management. The work started in the 1970ies, and results were published towards the end of the decade [3, 4]. Since then, computer capacity has greatly improved. In the early days of the model, the results would be ready the following day. At present, the calculations are practically instantaneous and may be performed on a laptop; anytime and anywhere.

Several papers have presented mathematical models for the study of Söderberg electrodes [5, 6]. Mc Dougall et al [5] presented a 3D model that was used to investigate stresses in the casing steel and the position of the baking zone when using different casing materials. For this study only direct current (DC) was used, which is probably an acceptable model simplification for the temperatures immediately inside the current clamps. Meyjes et al. [6] applied a model for both casing design and current clamp design. Also here only DC is used, but this probably also gives sufficient accuracy when temperatures just inside the clamps are considered. For temperatures below the clamps the alternating current (AC) versus DC will give large differences. When applying only DC, the skin effect will not be taken into account. This will give more current in center of the electrode and hence higher center temperatures than what is realistic. An important application area for the model presented in this paper is the study of thermal stresses during shutdown and start-up of furnaces. In this aspect, it is of utmost importance to include the electromagnetic fields generated due to AC in the current calculations.



**Figure 1:** Calculated temperature and current densities in electrodes with AC vs DC. Both are 1.7 m dia electrodes for FeSi with normal electrode current of 110 kA

After a furnace stop, the highest risk of electrode breakage is typically short time after full load is reached. This corresponds well to the peak stresses calculated by the model. These initiated a work of optimizing shutdown procedures. For instance, a short stop today rarely leads to breakage, because we know that the electrode should be powered up fast rather than continue to be cooled by slow heat-up.

Today, many electrodes are operated at high load, even above what is normally considered as "maximum" load for a given electrode dimension. This leads to high stress on the electrode and the process, and very little margin for error or imperfections in the electrode management. Operation

difficulties on large, high load electrode units will also be more costly, especially in terms of lost production potential.

With a validated mathematical model, it is possible to search for optimal operational procedures without expensive trial and error. It can increase understanding of underlying mechanisms, and assist in the work of continuously improving furnace operation and product output.

In previous publications [1, 3, 4] Elkem has shown how the mathematical models may be applied to simulate influence on baking zone position by parameters such as slipping rate, current density, steel casing thickness and material properties. Thermal stress during shutdowns has also been studied earlier, and the influence on stress level by the parameters electrode current, slipping rate, shutdown duration, current recovery time etc. has been presented.

This paper is a continuation of the previous work on thermal stress. We will discuss how the Elkem models can be used to improve understanding of thermal stress mechanisms, and how this may be interpreted in terms of operating procedures that will minimize risk of costly electrode breakages.

## **2. MODEL DESCRIPTION**

### **2.1. Introduction**

Elkem Carbon's 2-dimensional electrode models have a long history. A model computing the stationary temperature distribution for direct current (DC) was implemented in 1971. Later, alternating current (AC), dynamic temperature evolution, and the corresponding mechanical stresses have been included. The code has been updated at various points in time, and is now implemented as a user friendly system that is actively applied to diagnose customers' electrode problems, and to supply vital input for sound operation.

### **2.2 Model basics**

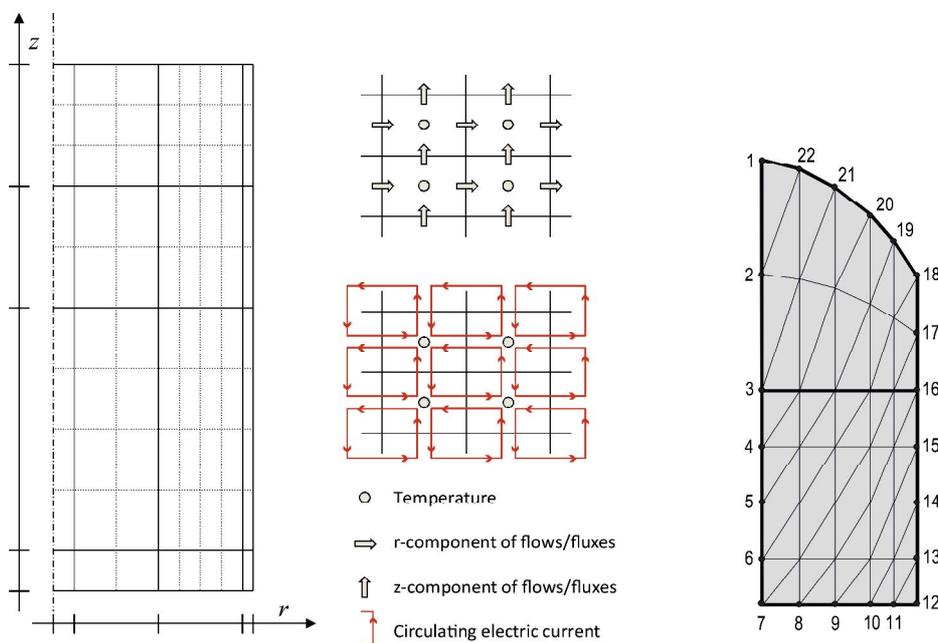
The models assume 2-dimensional, axially symmetric conditions. The finite difference method has been applied for the thermal and electrical equations. The computational domain is then sectioned into a rectangular grid, where the temperature is computed at the center of each cell and the heat flow in the r- and z-directions are defined at each cell boundary, c.f. figure 2. Control volume integration has been applied to derive the discrete equations, c.f. for instance Patankar [7].

The electric computations apply the quasi-static version of Maxwell's equations, assuming harmonic variation in the time domain for a specified AC frequency. Circulating currents between 4 neighboring cells have been chosen as the primary electric variables to be solved for. The current between two nodal points is then found by superposition of two circulating currents. This choice simplifies the equation system and the solution procedure significantly.

An Eulerian frame of reference is applied for the initial stationary simulations, where the average slipping rate is included in the thermal computations as a continuous material flow. Mathematical analysis has shown that this term is of vital importance, unless the slipping rate is very low, c.f. Halvorsen et al. [8], where such analysis is applied for the composite Persson type electrode.

A Lagrangian coordinate system is then applied for the dynamic temperature computations, i.e. the computational grid follows the electrode motion due to slipping and holder movements. After a dynamic temperature simulation, the corresponding quasi-static time evolution of the mechanical stresses can be computed. The finite element method is applied. Typical geometry is shown in figure 2. The upper boundary is given by the baking zone isotherm from the thermal

simulation. Normally the 500 °C isotherm is applied. It is sufficient to include only the baked carbon electrode in these simulations. In the fin region the steel will soften and then melt. The electrode can then comparatively easily expand or contract in the angular direction. Hence, we assume zero angular stress in this region.



**Figure 2:** Model discretization: Principal finite difference grid for temperature and electric computations (left), location of temperatures and fluxes (center), and typical finite element grid for stress calculations (right)

### 2.3. Boundary conditions

For the thermal computations the user specifies the following boundary conditions: ambient temperature, heat transfer coefficient for convective heat transfer, and effective emissivity. The parameters are specified at user selected locations. The program can handle linear variations and abrupt changes (steps) in both space and time. Below the holder the boundary conditions are applied in a spatially fixed coordinate system, while the conditions follow the electrode movements in the upper part. For the electric equation it is assumed that the current enters the electrode at the location of the contact clamps and leaves through the bottom of the electrode. Contact resistances that can vary linearly and/or in steps are specified towards the clamps and at the bottom.

The largest mechanical stresses in the electrode are due to temperature variations. But the program will also account for the electrode weight and the pressure of the soft paste at the baking zone. The external reaction force that will counteract the weight, is distributed between the holder region and the bottom according to the user's input.

### 2.4. Irreversible material data

The electrode paste is transformed as it is heated. The material properties like electric and thermal conductivities, Young's modulus, coefficient of thermal expansion, etc., depend both on the temperature and the highest temperature that has been attained.

## 2.5. Model validation, parameter adaptation

The temperature distribution computed by the model depends on boundary conditions that are not easily measured. To validate the model, and find appropriate values for the boundary conditions, temperature measurements inside the electrode are strongly advised. A number of steel tubes, typically 5-10 can be mounted at the top of an electrode. The tubes are extended along with adding new casing sections. When the bottoms of the tubes have reached a suitable distance below the baking zone, thermocouples are inserted into the tubes. The temperatures are then measured at a number of heights within the electrode. This supplies a partial inner temperature distribution, and the input boundary conditions can be adapted so that the computed temperature distribution will correspond to the measured one.

## 2.6. Thermal stresses during transitions – Time plot

When a solid body that can expand freely is uniformly heated or cooled, an initial stress-free state will be maintained. But heating or cooling will normally create temperature differences. Then various parts of the body will expand or contract differently. The corresponding non-uniform strains create internal mechanical stresses, called thermal stresses.

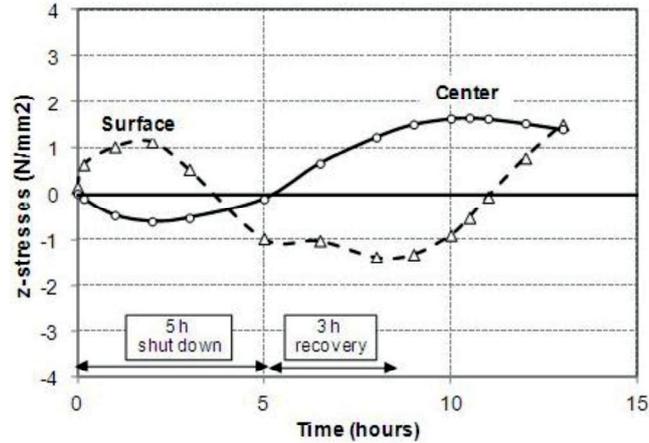
The conditions within an electrode are more complex. Along the baking zone at some 500 °C, there will only be a small stress in the solid electrode, due to the pressure from the unbaked paste. Then, as the electrode is further heated, the carbon material first shrinks for some time, before it follows a normal thermal expansion. Internal stresses are established during this process. Simulations at Elkem Carbon have revealed stresses above the tensile strength of the electrode during stationary operation. As electrode breakage does not occur during steady operation, we have concluded that these stresses are released to a large degree, e.g. by micro cracks. As a practical approximation, we assume that the electrode is stress-free during steady operation.

Consider a typical, operational shut down: The electric current is turned off, and the temperatures start to drop. The electrode is cooled from the outside, and the temperatures will decrease most quickly along the periphery. Hence, the electrode will shrink more in the periphery than in the center. A tensile stress will then build up at the periphery, and a compressive stress in the center. As the steady state temperature was higher in the center, the temperature drop will, after some time, be higher here. Then the stress state will be reversed, i.e. tension in the center and compression at the periphery. This condition is enhanced after the current is turned on, as the temperatures will increase more rapidly along the periphery (AC and skin effect).

Extensive simulations have shown that the critical tensile stress in a Söderberg electrode will occur in the vertical direction, either at the center or along the periphery. To supply a quick view our computer code will therefore identify two critical points: one along the center line and one at the periphery where the highest tensile stress is attained. A time plot of the evolution of the z-stress in these two points is automatically generated c.f. figure 3.

The given case represents a 1.7 m electrode current of 110kA. Calculated stress after 5 hours shut down and 3 hours recovery are shown.

The material properties used in the model input will influence the results for both temperatures and thermal stresses. It is crucial to use correct data also at elevated temperatures. A good model using incorrect data can give misleading results. The results and conclusions in this paper are therefor only valid for electrodes having properties as obtained with Elkem paste. Other electrode pastes, having different properties, can very well give different temperatures and stresses. The suggested procedures given in this paper can therefore not automatically be applied in electrodes using other pastes and hence other optimized procedures.

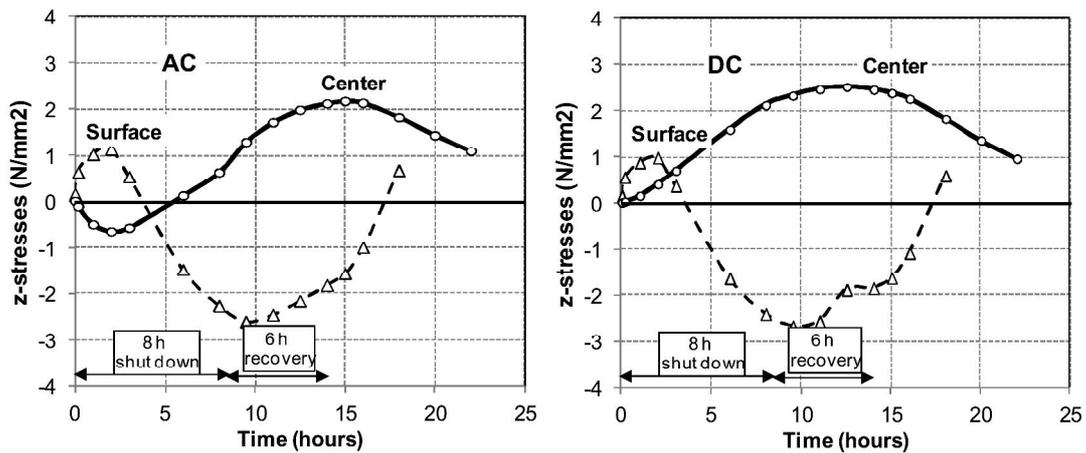


**Figure 3:** Typical time plot of the z-stress in two critical points, one in the center and one at the periphery of the electrode. The highest tensile stresses at the respective locations are attained at these points. The maximum tensile stress on the electrode surface occurs after about 2 hours ( $1.2 \text{ N/mm}^2$  - dashed line) and the highest tensile stress in electrode centre at about 11 hours ( $1.7 \text{ N/mm}^2$  - solid line)

### 3. DISCUSSION OF RESULTS FROM CALCULATIONS

#### 3.1. Stresses in electrodes with AC versus DC

Figure 1 shows the calculated temperatures and current density in electrodes with alternating current (AC) versus direct current (DC). The DC calculation gives higher temperatures in the electrode center. As a next step we can calculate and compare the thermal stresses formed during an e.g. 8 hours shutdown and 6 hour current recovery. The results shown in figure 4 demonstrate that the DC powered electrodes also get different thermal stresses during a shutdown.

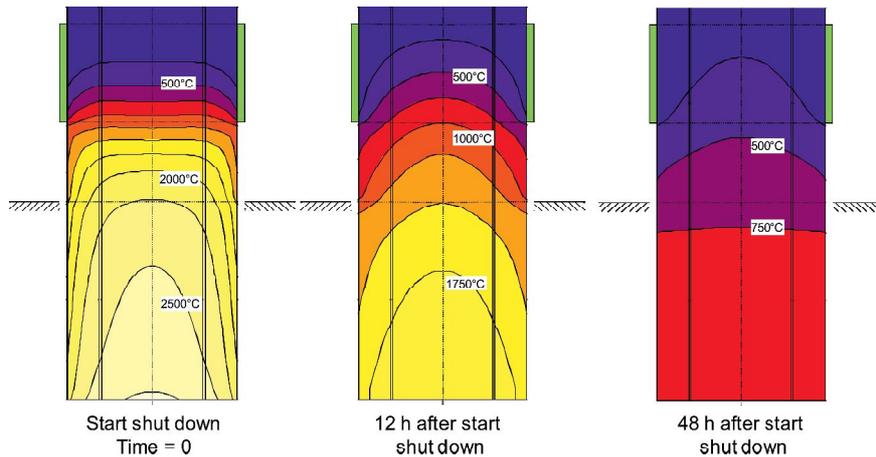


**Figure 4:** Time plot of the z-stresses in the two cases AC and DC. 8 hour shutdown followed by a 6 hour current recovery. 1.7 m dia electrodes for FeSi, 110 kA

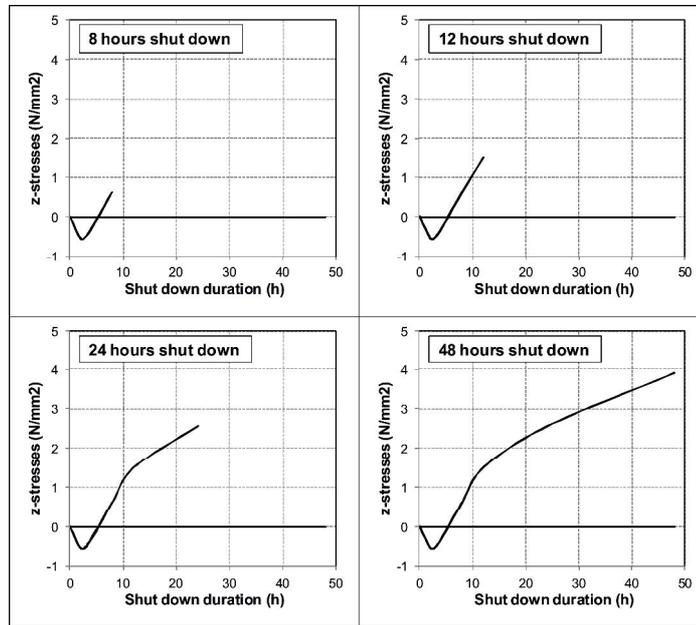
The warmer electrode center in the DC electrodes makes the potential cooling higher and results in higher stresses. All other stress calculations given in this paper are made for cases with AC.

### 3.2. Thermal stresses during a furnace shutdown

When the electrode current is shut off during a furnace stop, the electrode will immediately start to cool down, figure 5. The electrode will lose heat through the electrode surface, and heat will flow from warmer to colder parts of the electrode. These changes in temperature will generate various degrees of material contraction, hence thermal stress in the material. The extent of cooling will depend on how well the electrode is covered (insulated), and the duration of the stop. A long shutdown will always give more cooling and higher thermal stress compared to a short shutdown.



**Figure 5:** Cooling of a 1.7 m dia electrode during shutdown. Electrode current before shutdown was 110 kA. Calculated as a covered electrode



**Figure 6:** Thermal stress in center of a 1.7m dia covered electrode during shutdowns of various durations. Additional stress generated during power recovery is not included

The curves shown in figure 6 represent thermal stress formed during a shutdown, i.e. before the electrode current is applied. These stress levels are therefore independent of the current recovery

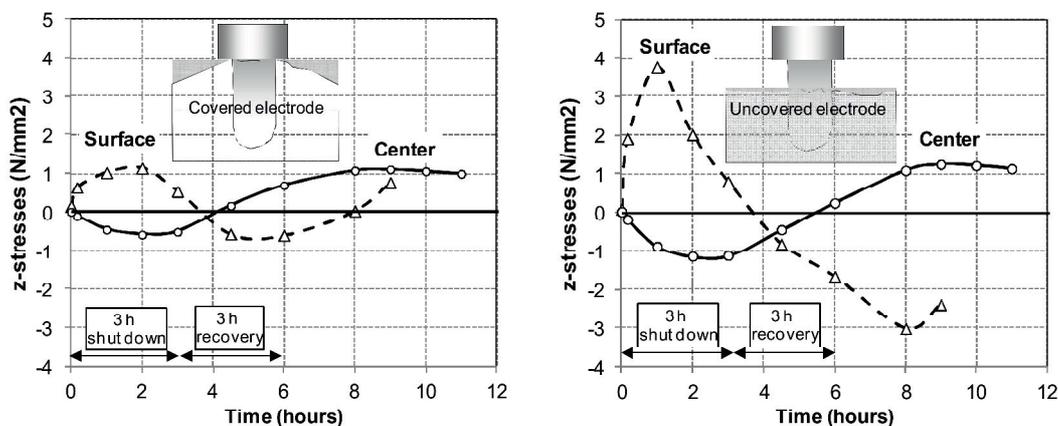
that follows after the shutdown. The figures show that long shutdown durations will generate higher stress levels than shorter shutdowns.

Thermal stress generated during a furnace shutdown (i.e. before start of current recovery) can only be influenced by the current level before the stop, or by controlling the degree of heat loss during the stop.

### 3.3. Covered versus uncovered electrodes

The stresses illustrated in figure 6 are generated as a result of the electrode cooling during a shutdown. The cooling of the electrode surface starts immediately after the current is turned off, and the most exposed area will be inside the current clamps and the area between the current clamps and the charge mix. During cooling, the electrode material will contract and tensile stresses in vertical direction are formed. This can be observed in the time plot of the z-stresses as a peak after 1-2 hours in the surface curve figure 3. By reducing the heat loss from the electrode, this peak may be lowered. This can be done by covering the electrode with insulating material (e.g. stone wool type), or by the charge mix. If charge mix is used, the best result is of course gained if the charge material is not cold. Since the cooling starts immediately after the current is turned off, it is important to cover the electrode surface as soon as possible. For a planned shutdown, this should be prepared in advance.

In figure 7 we have compared the resulting stresses in covered versus uncovered electrodes. The effect is substantial. It should also be mentioned that it is not only the stresses on the surface that are reduced by covering the electrode surface. As can be seen from figure 7, the tensile stress in the center of the electrode is reduced approximately 10% for the case with covered electrode. For longer shutdowns, proper covering of the electrodes is considered to be of crucial importance.



**Figure 7:** Calculated time plot of z-stresses in covered versus uncovered electrodes. 1.7 m dia electrodes for FeSi with 110 kA electrode current

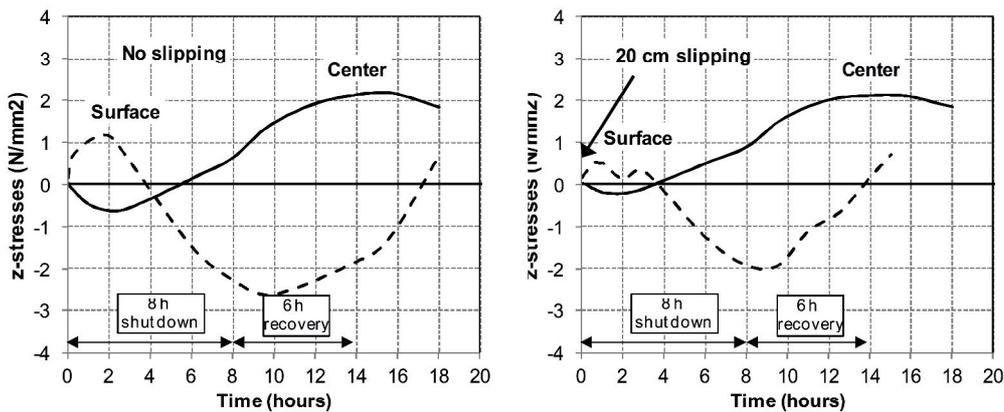
### 3.4. Additional slipping during the shutdown

Another method to further reduce the cooling of the electrode surface is to make a slipping of 5-30 cm just after the power is turned off. The electrode will then be moved downward in the charge mix where the temperatures are higher and hence the cooling will be lowered. An additional effect is that the baking zone will be lowered so that the clamps are filled with more unbaked paste.

Unbaked paste has low thermal conductivity and will lose less heat to the water in the clamps. The result of this reduced cooling is a lower stress peak on the electrode surface c.f. figure 8.

In addition to the reduced stress on the electrode surface there is also a small reduction of stresses in the center. For uncovered electrodes we have found that this reduction in center stress is significant.

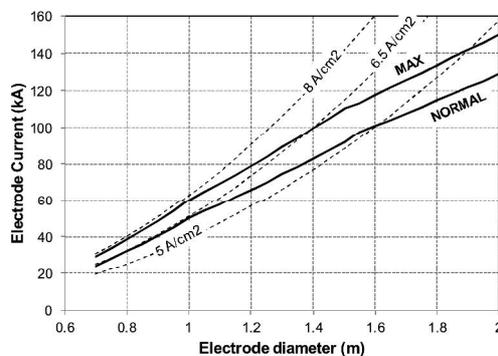
If the electrode has been slipped during shutdown it can be required to be more careful during the power recovery. When unbaked paste is lowered into the lower end of the clamp, there will not be any baking of this material during the shutdown. Unbaked paste in this area can be a limiting factor for the level of the start current. In such cases the start current should not be higher than the current carrying capacity of the actual steel casing. In addition, the recovery rate should allow for a proper baking of the paste that was slipped out from the current clamps.



**Figure 8:** Additional slipping (20 cm) at the beginning of the shutdown. 1.7 m dia covered electrode. Normal slipping is 2.5 cm/h at 110 kA

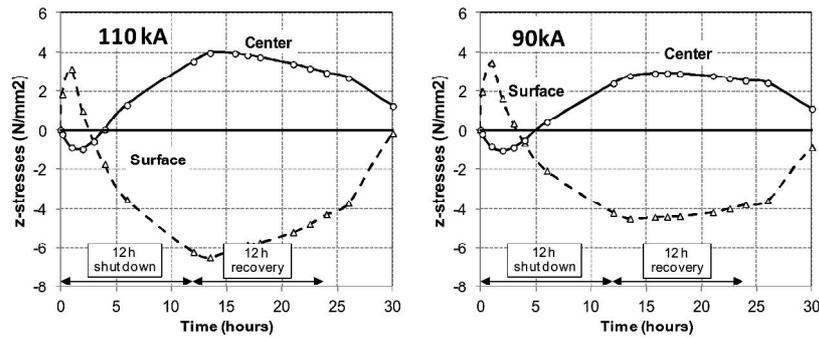
### 3.6. Electrode current level and thermal stresses

Electrodes with high current load are warmer than electrodes where low current is applied. Small electrodes have a larger surface/volume ratio than larger electrodes, and hence a larger relative heat flux through the electrode surface. This also explains why it is possible to operate smaller electrodes with higher maximum current density than large electrodes, as illustrated in figure 9. A normal operating current density in a 1 m electrode is 6.5 A/cm<sup>2</sup> while a 1.7 m electrode will have a normal current density below 5 A/cm<sup>2</sup>. In many cases it is possible to operate the electrodes at the line called “MAX” in figure 9.



**Figure 9:** Maximum and normal electrode current load in Söderberg electrodes

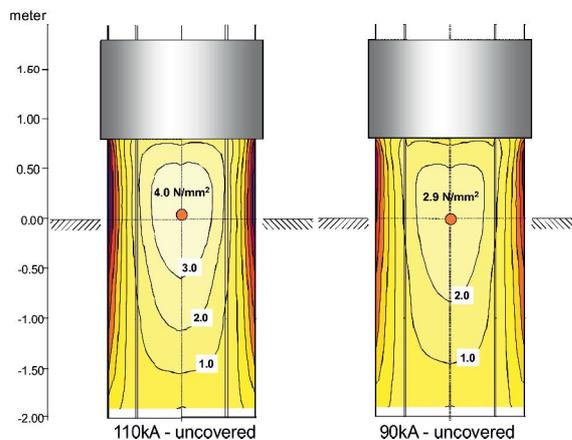
The electrodes will be very warm, but as long as there are no interruptions, the electrode can function well. The potential problem arises when the power is changed or turned off. The risk of having a hard breakage is then high, especially if the shutdown duration is more than 8 hours and if the electrodes are poorly covered. To illustrate this effect we have compared the thermal stresses in a 1.5 m electrode with electrode current 110 kA versus 90 kA, in a case with 12 h shutdown followed by 12 h power recovery. The critical tensile stress in the center of the electrode increases from 3 N/mm<sup>2</sup> to 4 N/mm<sup>2</sup> when electrode current is increased from 90 kA (= “normal”) to 110 kA (= “max”), c.f. figure 10.



**Figure 10:** Time plots comparing z-stresses during a 12 hour shutdown in 1.5 m dia electrode with operating current 110 vs 90 kA. Uncovered electrodes

In order to counteract the formation of such high stress levels in high loaded electrodes (i.e. operated at “max” current) it is possible to reduce the current load to “normal” level 48 hours ahead of a planned shutdown. The temperatures will then be stabilized on a lower level and a large part of the electrode that has been exposed to the highest temperatures will be shifted downwards to a safer position below the level of the charge mix. Several plants have this as standard practise before a planned shutdown.

The z-stress level in the electrode with 110 kA is considered to be so high that a breakage is likely to happen. In case the shutdown is unplanned, it has not been possible to reduce the load as a preparation. The most important action would then be to try to insulate the electrodes as well as possible. If the shutdown is long, generation of high stresses is inevitable and there is a pronounced risk of having a breakage.



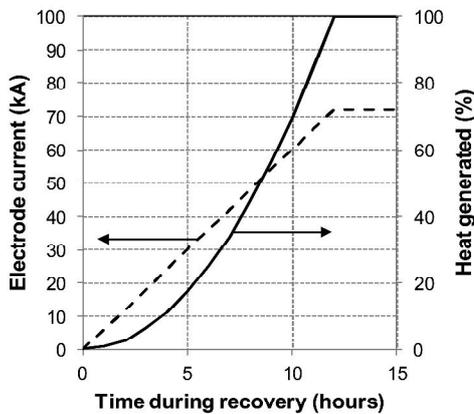
**Figure 11:** Isoplots of the vertical stress component in the cases shown in figure 9. At time 15:45 h

### 3.6. Current start set point

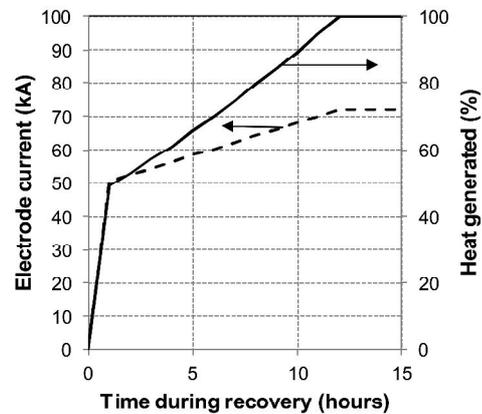
When powering up after a shutdown, it is important to use correct start level of the current. Heat generation is a function of electrode current in the second power. If the electrode current is increased linearly from zero to normal current, the heat generation will follow a curve as shown in figure 12.

The heat formation in the beginning of the recovery is very low and can even be lower than the heat loss from the electrode. This gives continued cooling rather than heating, and will in most cases contribute to increased stress levels. In general it is therefore better to start the recovery at a higher current, figure 13. This will counteract further cooling, and reduce the time needed to recover normal temperature conditions. For the examples in figure 14 we can see that lowest maximum stress is obtained in the case with the highest start-up current. This demonstrates the effect of continuation of the cooling if too low start current is applied.

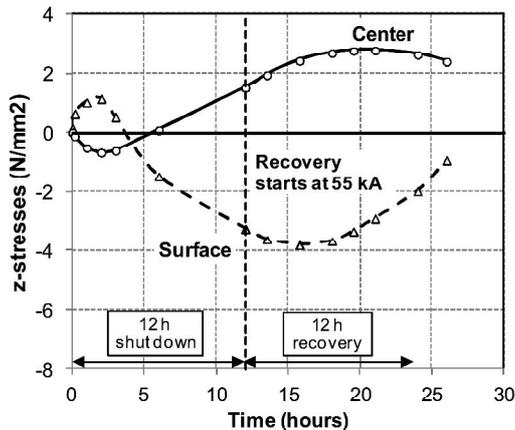
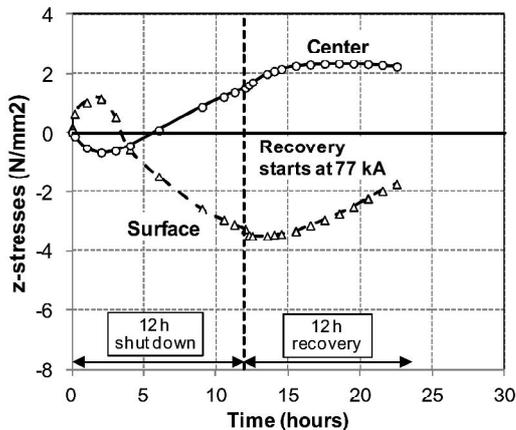
In case the electrode has been slipped when the shutdown was initiated it can be necessary to account for unbaked paste below the current clamps when the furnace is energized again c.f. chapter 3.4.



**Figure 12:** Heat generation in an electrode during recovery, showing linear current increase from 0 kA to normal current. 100% = heat generation at normal load



**Figure 13:** Heat generation in an electrode during recovery. Current starts on 70% of normal current level. 100% = heat generation at normal load

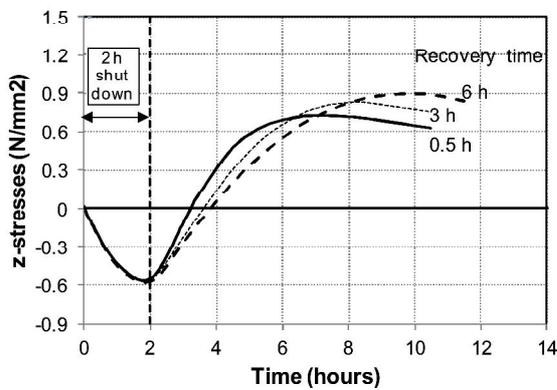


**Figure 14:** Time plots of z-stresses for two cases where current at start-up is 70% (77 kA) or 50% (55 kA) of normal electrode current (110 kA). Both cases represent a 12 hours shutdown followed by 12 hours current recovery. 1.7 m dia covered electrode

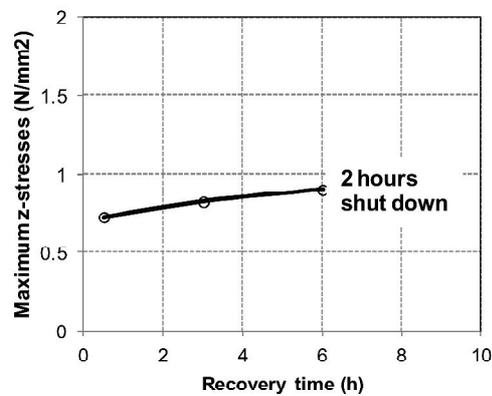
3.7. Current recovery time

A general rule for the recovery time is that short shutdowns should be recovered fast, while long shutdowns require longer current recovery. The definition of short and long shutdown depends on the electrode size as well as the current load. An example is shown in figure 15, where a short shutdown of 2 hours is illustrated. The lowest stresses are obtained at the fastest recovery. Slow recovery will only cause the electrode to continue to cool down, ref. chapter 3.6.

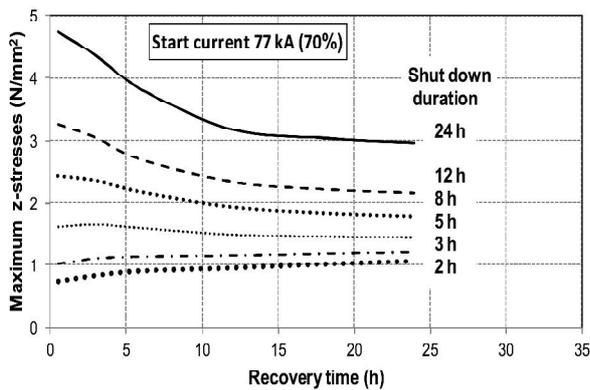
The highest stress value generated at each of the recovery times are used to form the graph in figure 16. This maximum z-stress curve gives information on both the stress level as well as which recovery time is the most beneficial. If we increase the amount of information further by applying several curves, each one representing a given shutdown duration, we get the very useful stress diagram for a given electrode, figure 16. Such diagrams make a valuable tool for optimizing the shutdown procedures for an electrode.



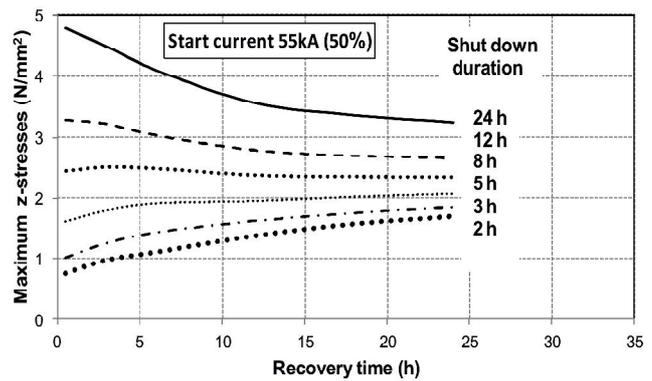
**Figure 15:** Thermal stress in center of a 1.7 m dia electrode after a 2 h shutdown. Various recovery times are applied. Stress values for the electrode surface are not shown. 110 kA normal current, slipping 2.5 cm/h



**Figure 16:** Maximum z-stresses generated after a 2 hour shutdown at various recovery times



**Figure 17:** Maximum stress following various shutdown durations and current recovery times. Covered 1.7 m dia electrode, with current recovery starting at 70% of the normal current



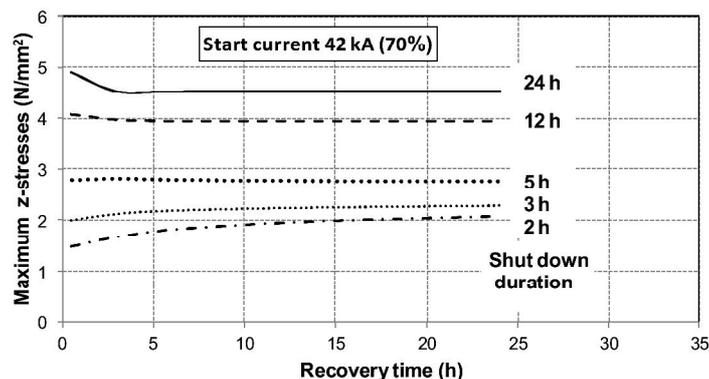
**Figure 18:** Maximum stress following various shutdown durations and current recovery times. 1.7 m dia electrodes. Current recovery starts at 50% of the normal current

From figure 17 we can conclude the following for a 1.7 m covered electrode. For shutdowns up to 4 hours, the generated thermal stress will in general be low. Fast current recovery can be applied, and will minimize the stresses. For shutdown durations around 5 hours the recovery time will not influence the stresses significantly, and the recovery can also be fast. For the longer shutdowns it is not possible to avoid that high stresses are formed. In these cases (and especially if experience shows that a breakage is likely to occur) a slower recovery rate can be used to reduce the maximum stress.

The same calculations have been repeated, but this time with a lower level start-up current. The results given in figure 18 show that in terms of thermal stress, it is not beneficial to start the recovery at only 50% of the normal current.

A similar diagram can be made for smaller electrodes, figure 19. Fast recovery following short shutdown durations is also beneficial for the small electrodes. For the longer shutdowns we can, however, say that recovery extending 5 hours will not reduce stresses. The general rule for such small electrode would then be: fast recovery for shutdowns up to 5 hours. For shutdown durations above 5 hours the recovery time can be 5 hours.

In case the electrode was slipped out from the current clamps during the beginning of the shutdown it is again necessary to evaluate if the start current should be limited, c.f. end of chapter 3.4.



**Figure 19:** Maximum stress following various shutdown durations and current recovery times. The case is calculated for a 1.1 m dia electrode, with current recovery starting at 70% of the normal current (60 kA)

#### 4. CONCLUSIONS

- Mathematical modeling is a powerful tool for understanding thermal stress in Söderberg electrodes, and is valuable in order to find optimum shutdown procedures.
- The results presented in this paper are based upon the material properties of Elkem electrode paste. Other pastes, having different properties, will behave differently and will not have the same optimized procedures.
- The current distribution in Söderberg electrodes operating with AC or DC will be significantly different. A DC model is inadequate for normal (AC) conditions to study temperature distributions and the corresponding thermal stresses.
- The thermal stresses in an electrode during and after a shutdown are highly influenced by the shutdown duration. The stress levels increase with longer shutdowns. Proper planning can shorten the duration of a shutdown, which will reduce the risk of a hard breakage. If possible, it can be beneficial to make two shorter stops rather than one longer.

- For long shutdowns, more than 12 hours, the generation of tensile stress in the center of the electrode cannot be avoided.
- Proper thermal insulation (covering) of the electrode surface reduces the stresses both on the surface and in the center. Such covering should be carried out as soon as possible after the power is turned off.
- An electrode slip once the power is turned off will also reduce the heat loss from the electrode and reduce the stresses.
- If electrode breakages are experienced to be a problem, it can help to reduce current load 48 hours prior to the start of the shutdown. Obtaining deep electrode penetration during this period is also advantageous.
- Current recovery should start at 70% of the normal electrode current. If the electrode was slipped 5-30 cm during the beginning of the shutdown, the start current should be lower than the current carrying capacity of the steel casing.
- For short shutdowns up to 4 hours, the current recovery time should be fast.
- For long shutdowns, and if breakages are experienced to be an issue, the tensile stresses can be reduced by applying a longer recovery time. For small electrodes (1.1. m diameter) the current recovery for long shutdowns can still be made within 5 hours.

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