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THERMAL EVENTS OF THE EARLY LIFE OF AN ALUMINUM ELECTROLYSIS CELL

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Abstract

The efficient and long operation of an aluminum reduction cell strongly depends on the early period of the pot-life. In order to have a record of the events of the cell structure's thermal state, the temperature in the sidewall was monitored. The unsteady thermal events were compared with the cell voltage as well as correlated with various events during the early pot-life.

We found that with the proper positioning of the thermocouples, major events can be detected. Apart from the detection of the effect of different events along the sidewalls, the temperature signals can provide further information. We propose various signal properties such as frequency content, amplitude and phase information, which can be exploited in the thermal diagnostics of an electrolysis cell.

With in-situ measurement examples we demonstrate that the temperature signal of the sidewall provides useful information in both operation and the diagnostics of the aluminum electrolysis cells.

Introduction

The first weeks of operation are known to strongly influence not only the lifespan, but the overall performance of an aluminum electrolysis cell. The preheating, the pouring of bath and metal and the ramp-up period in the early life of a cell have their unique impact on the later performance. To control the operational parameters in this critical period the thermal state of the cell is monitored through continuous measurement of the cathodes and later the bath temperature. Additionally, the containing steel shell surface temperature is measured occasionally [1].

It is widely accepted that the service life of an aluminum electrolysis cell is mostly limited by the performance of the pot sidelining [2, 3]. Many cells are stopped due to the insufficient integrity of the sidewalls resulting in the leakage of the bath or the liquid aluminum. Various improvements have been realized since the early cell constructions with solid monolithic walls through new sidelining materials and material combinations [4]. However, the continuous increase in the cell load demands a more active control of the sidewall thermal loads that is beyond the design period of the cell. The effects of routine operations such as an anode change or events like anode effects on the sidewalls are also of the interest in order to better understand the thermal load of the pot structure and to aid further developments.

Although the shell temperature might indicate the thermal state of the sidelining but it may also imply false information. Due to the occasional separation of the shell from the sidewall blocks these measurements can underestimate the general thermal load of the sidewalls. In order to provide direct information on the sidewall temperature, thermocouples were embedded in the sidewall blocks of a prebake aluminum electrolysis cell. We continuously measured the temperature changes during the early period of the cell operation to provide information on the thermal loads on this critical structural area.

Experimental work

The measurement campaign was carried out on an industrial point fed prebake electrolysis cell of Rio Tinto Alcan over the course of several months. Appropriately protected thermocouples were inserted into the sidewall blocks. Before installation, all thermocouples were calibrated; measures were taken to minimize the thermal contact resistance between the tip of the thermocouples and the material of the sidewall block.

TCs were inserted in both the up- (TC+) and downstream (TC-) sidewalls of the reduction cell, located at an average of 130 mm above the bath-aluminum interface. The distance from the wall-freeze interface was about 50 mm, the actual measurement locations are shown in Figure 1.

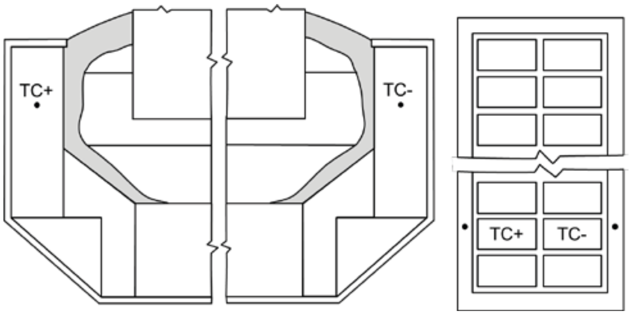

Figure 1. Position of the thermocouples in the electrolysis cell

The TC signals were recorded with a sampling interval of one minute using the standard data acquisition system of the plant. Along with the temperatures, the cell voltage was also recorded, in the present paper the mean values of the signal during one minute are displayed.

The recorded data was loaded into Matlab (MathWorks, Natick, Massachusetts, U.S.A) to compare, analyze and visualize the temperature histories together with the cell voltage.

Thermal history of the early pot-life

In this section we introduce the resulting temperature variations in the sidewall in the three periods of the early pot-life: the preheating, the feeding of bath and aluminum and the ramp-up period.

Preheating

The goal of the preheating is to reach a stable thermal gradient in the pot with surface temperatures close to the operating temperature [1]. In the present case the cell is resistor-baked with the use of a coke bed under the anodes.

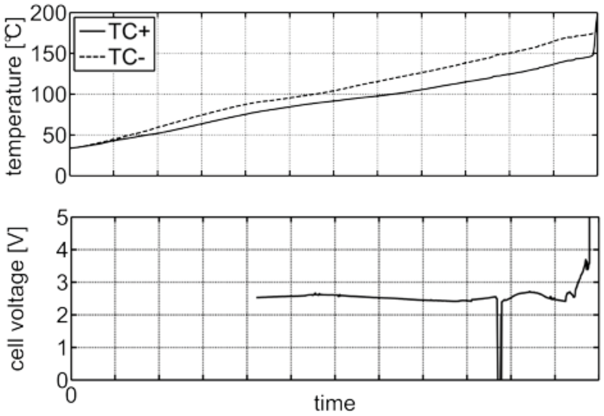

Figure 2. Sample temperature signal of the sidewalls and corresponding cell voltage during the preheating

As Figure 2 shows the preheating period results in a sidewall temperature between 150-180°C. The recorded signal shows that the rate of temperature increase in the sidewall is insensitive to small voltage variations during preheating.

Introduction of bath and aluminum

The bath introduction is the second step in the cell start-up sequence helping the cleanup of the excess materials left there after preheating while the cracks in the pot structure are sealed by the freezing bath. To assure these after the bath introduction the cell is running with just the bath, therefore, this stage is called the bath soaking period [1]. The effect of the bath and metal introduction can be observed in Figure 3 along with the resulting sidewall temperatures in this rapidly changing thermal situation.

The bath introduction along with an increased cell voltage results in a sudden temperature rise in the sidewalls, the rate of temperature increase is one order of magnitude higher in average than during the preheating. The initial increase is even higher, about three times the average value. It is interesting to mention that the upstream sidewall has a more intense temperature increase leading to an even temperature between the two sides of the cell temporarily.

The same effect is visible after the aluminum introduction following the bath soaking period. While the downstream temperature increases slowly and monotonously, the rate of the increase of the sidewall temperature upstream doubles. This rate of change results in higher temperatures on the upstream side after the aluminum introduction. During this period slightly red shell color was reported on the cell. The sidewall temperatures reaching 650-700°C agree with this observation. According to the recorded signal the temperature gradually decreases to about 550-600°C and starts to increase again.

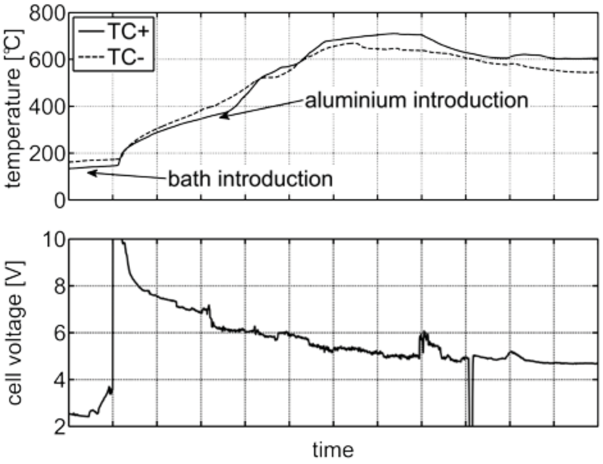

Figure 3. Sample temperature signal of the sidewalls and corresponding cell voltage during the bath and aluminum introduction

Comparing the cell voltage and the recorded temperature signals we can conclude that there is a significant lag between an event and its effect on the sidewall. This can be observed at the moment when the voltage starts to slowly increase in Figure 3 or at the moment of the aluminum introduction causing a sudden voltage drop. Both have an effect on the upstream temperature signal which appears approximately one hour later. The downstream signal appears to be less sensitive to these effects.

Ramp-up period

During the ramp-up period the bath composition is brought to the production norms. This period is characterized with typically high bath temperatures [1], which in our case results in high sidewall temperatures (Figure 4).

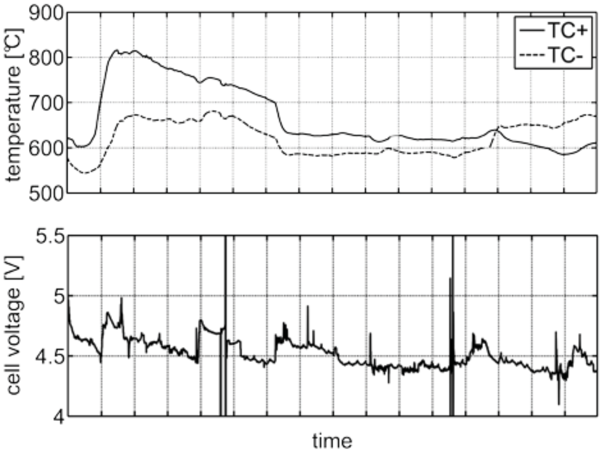

Figure 4. Sample of several days of temperature signal of the sidewalls and corresponding cell voltage during the ramp-up period

Following a peak temperature and its moderate decrease after the aluminum introduction the temperature starts to rise again leading to a high, ~130°C temperature difference between the two sidewalls sections. The available signal shows that the higher wall temperature can be associated with slightly increased mean cell voltage. The sidewall temperature settles around 600°C which is about 50°C above the normal production temperature.

Thermal effect of common events

Several operational changes affect the thermal balance of an electrolysis cell. These can occur with hourly frequency such as the alumina feeding, with daily frequency as anode changes or occasionally such as the unintended anode effects. In this section we present the effect of an anode change and a series of anode effects on the sidewall temperature.

Anode change effects

The change of an anode is known to bring significant thermal disturbance in the cell operation. Once an anode is removed, the bath is directly exposed to the environment, loosing heat by radiation. The insertion of the new and cold anode then acts as a thermal sink in the system with its significant thermal mass. The bath first solidifies on the new anode surface isolating it both electrically and thermally, the heat generation by the joule effect is therefore reduced in its vicinity. Aune et al. [5] inserted TCs in anodes in a series of experiments and found that it takes about 40 hours to reach a stable temperature inside a newly set anode. Additionally, he found significant temperature decrease (20°C) in a neighboring anode during the heating-up of the new anode.

The sidewall temperatures correspond with the findings in neighboring anodes. In Figure 5 it can be observed that the upstream sidewall, which is the closest to the changed anode, cools down significantly. An approximately 50°C temperature decrease is recorded and the effect of the new anode lasts about 24 hours. The time of the cool-down and heat-up is about of the same length, approximately 3 hours. The signal of the downstream wall shows well that the effect is localized as it is much less affected by the anode change on the opposing side of the cell.

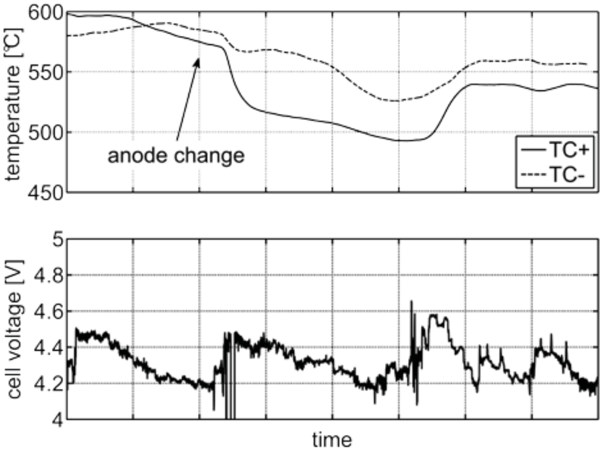

Figure 5. Temperature signals of the sidewalls and corresponding cell voltage before and after the change of an anode in the vicinity of TC+

Thermal history of anode effects

The locally poor alumina concentration may lead to an anode effect resulting in rapidly increased heat production. The anode effect poses a high thermal disturbance to the pot structure and causes the overall instability of the cell [6]. Figure 6 shows the effect of this violent thermal event on the sidewalls of the reduction cell.

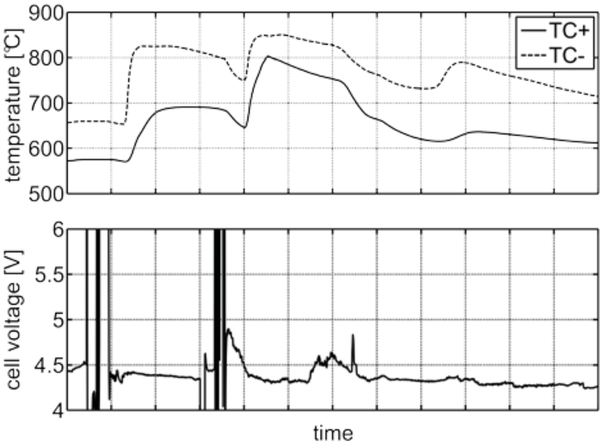

Figure 6. Sample temperature signal of the sidewalls and corresponding cell voltage while a series of anode effects occur

The cell voltage clearly demonstrates in Figure 6 that during the sampling period two anode effects disturbed the operation of the cell. As the temperature recordings show, these posed an extreme thermal load on the sidelining. Each event rapidly increased the sidewall temperature by about 100°C resulting in 800 and 850°C maximum temperatures of the walls. The high temperature increase led to a 100°C temperature difference between the two sides over the course of a full day.

Information content of the temperature signals

Additionally to the magnitude of the temperatures further information might be extracted from the recorded TC signals. In order to reveal the basic mechanisms, we make few simplifying assumptions about the physical phenomenon. In the current case we assume that the signal passes in a semi-infinite solid wall, the surface of which is excited with a combination of harmonic temperature signals. The schematic diagram of this simplified case is given in Figure 7.

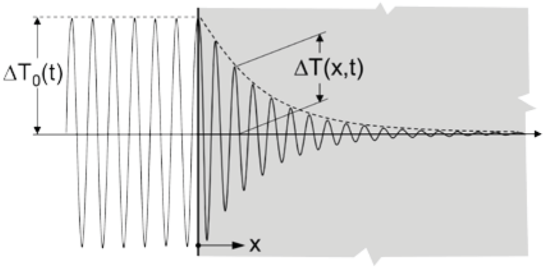

Figure 7. Schema of the propagation of a harmonic temperature signal in a semi-infinite solid

The solution for the temperature distribution in a semi-infinite solid resulting from a harmonic surface temperature excitation is known in a closed form [7], the resulting distribution is given in Equation (1).

$$\Delta T = \Delta T_0 \, e^{-\sqrt{\frac{\omega}{2\alpha}}x} \cos(\omega t - \sqrt{\frac{\omega}{2\alpha}}x) \qquad (1)$$

In Equation (1), ω represents the angular frequency of the harmonic fluctuation, α is the thermal diffusivity of the solid, x and t are the spatial and temporal coordinates respectively. If we accept that the measured temperature signal behaves according to the assumed model and therefore according to Equation (1) we can make further assumptions about the signal source and the signal propagation path.

Given a certain temperature fluctuation at a single frequency the signal at the fixed TC location will be more or less damped based on the length and the material properties along the signal path. Therefore, the temperature fluctuation amplitude carries information on the material thickness and thermal diffusivity. Equation (1) shows that the higher the frequency of the oscillation the more strongly it is damped. Thus, the frequency content of the measured signal can also act as an indicator of the wall material properties and wall thickness. Similarly, the phase delay can provide valuable information as it depends also on the material properties and on the TC location.

Harmonic content of signals

Figure 8 gives two examples of the lack and presence of higher frequency components in the sidewall temperature variations.

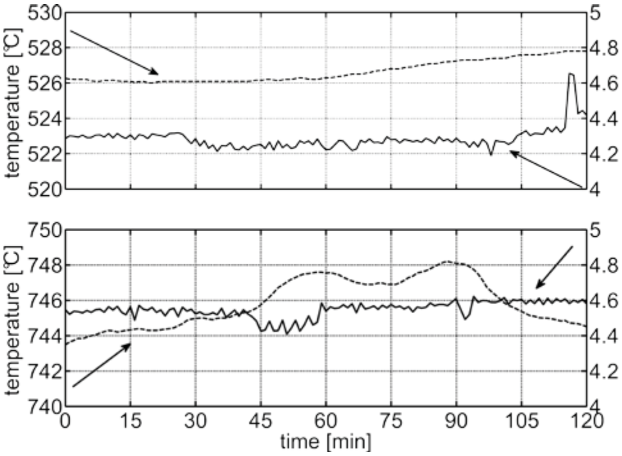

Figure 8. Two sample temperature signals of TC- with corresponding cell voltage signals, with lower (top) and higher frequency contents (bottom) (note the identically broad temperature ranges)

Although the cell voltage does not indicate higher frequency fluctuations, the temperature signals clearly show differences in their frequency content in the lower diagram of Figure 8. Additionally a higher average temperature is present in this case.

Relative signal amplitude and phase shift

In order to conclude about the reasons for the change of the amplitude and phase of a signal, a reference signal is needed. Ideally this reference would be the bath temperature in the proximity of the TC in the wall. Since this is not available, we compare the two temperature signals on the two sides of the electrolysis cell. This can provide information on the relative location of the source of the thermal event or about the relative thickness through which the thermal signal travelled. It is important to mention that in the present case we refer to the signal phase shift as the time difference between the characteristic points where the compared signals were measured. Although this is not identical with the phase of the simplified solution in Equation (1) they correlate well.

Figure 9 shows two subsequent anode changes with five days difference, the first one is closer to the upstream TC while the second is closer to the downstream TC. As it is visible in both cases, the temperature signal of TC- reacts faster, the shift between this signal and the thermal event in the bath is shorter than that of TC+. Still, the changes in the temperatures are higher in the TC signal closer to the location of the event. This suggests that while the signal amplitude change is more sensitive to the location of the thermal event, the phase relates more to the signal path. This agrees with the usually thinner freeze on the downstream side of the electrolysis cells.

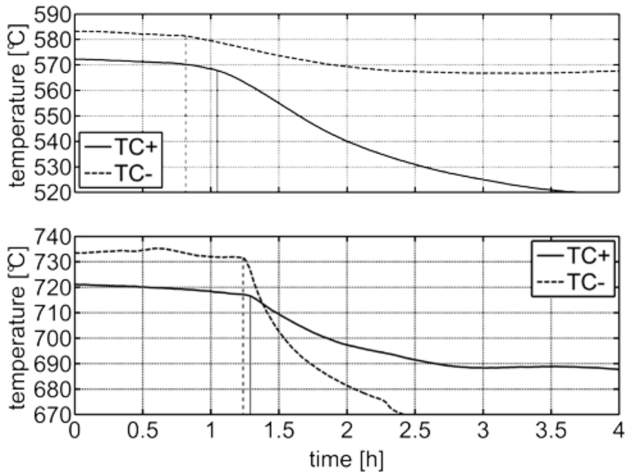

Figure 9. The effect of anode change near TC+ (top) or TC- (bottom)

Discussion

The current paper presents a study on the temperature changes in the sidewalls of aluminum electrolysis cells. Although the sidewall plays a significant role in the life expectancy of the cells its conditions are not followed continuously, only by occasional shell temperature and sometimes heat flux measurements. We inserted TCs in the two longitudinal walls of a prebake aluminum reduction cell and registered the temperatures over the course of several months. This covered the early period of the pot life and included the occurrence of thermal events like the anode changing and anode effects.

The recorded temperatures show clearly the variations of the sidelining temperature during the cell preheating. After the smooth sidewall temperature increase during the preheating, our records show the rapid increase with the introduction of the bath and the aluminum. Comparison of the two sides of the pot revealed a temporary difference in the rate of the two recorded wall temperature variations resulting from the bath and metal introduction. We suspect that the location of the injection of the molten bath and metal plays a role in the temporarily different temperature increase rates. During the ramp-up period after the temporarily high temperatures, the wall temperature settles at a moderately higher temperature than that of shown by the long term records. This effect is related to the usually higher bath temperature in this period of the pot-life [1]. Overall, we can conclude that this type of signal can serve as a record of the thermal history in the most critical part of the pot-life and even provide a feedback on the efficiency of the start-up procedure.

The effect of the anode changes on the sidewall temperature corresponded to those of previous temperature measurements carried out in anodes [5]. These are 50°C temperature drops in the neighborhood of the anode which is effective for about a whole day. We suspect that the local sidewall temperature change is not only the effect of the cold mass of the anode which acts as a heat sink but it is also associated with the local thickening of the freeze on the wall. We have shown that the thermal load during an anode effect is extreme on the sidewalls. The rapid increase of the temperature by more than 100°C imposes great stress on the sidelining and is undoubtedly associated with the significant thinning of the protective freeze layer. The two TC signals demonstrate the uneven temperature distribution on the two sides of the wall. The presented thermal history clearly shows that the cell events that arrive occasionally, may pose a much higher thermal load on the sidelining than that one would expect from bath temperature changes.

We presented a concept to extract additional information about the cell state based on the spectrum of the temperature measurements. We can show that the amplitude and the phase change depend on the path of travel of an unsteady signal. Studying the acquired temperature records we could identify periods of operation where higher frequency components appear in the signal, while there is no significant difference in the cell voltage fluctuations. Since the freeze supposedly has at least an order of magnitude lower thermal diffusivity than the sidewall, the lack of the frequencies due to the damping is mostly the result of travel of the signal through the freeze layer. Therefore, the higher the frequencies in the signal are, the thinner freeze layer we can assume. Similar information can be extracted from the different amplitude change and phase lag between the two TC signals.

Although these considerations are fundamentally qualitative, if the freeze thermal diffusivity can be found at least approximately, a quantitative estimate of the thickness is also possible. To this end the frequency content of the signal needs to be quantified, which is possible with a Fourier series expansion. Furthermore, as it was demonstrated in laboratory measurements, it is possible to identify an isothermal surface, such as the freeze boundary, using inverse methods based on temperature measurements in the sidewall [8]. Our in-situ measurements can be extended to this application. It has to be noted that any conclusion derived from the concept of a semi-infinite wall has a limited accuracy due to neglecting of factors such as nonlinear material properties or because the wall cannot be considered as semi-infinite below a certain value of frequency. Nevertheless, the approach presented here allows a deeper insight into the cell thermal state beyond a single bath temperature value, providing qualitatively correct information.

Conclusion

The measurement of the sidewall temperature was successfully executed in a point fed prebake aluminum electrolysis cell during several months. These measurements provide a valuable record of the thermal load of the pots sidelining during the start-up period and also in normal operation.

The temperature history along with the extracted information can serve as a diagnostic tool and provide a record for further developments of the electrolysis cells in terms of the thermal design. Additionally, the recorded temperature signals can be used to extract data about the overall state of the sidewall freeze and about the location of certain thermal events in the cell.

Acknowledgements

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