Controlling the Electrical Resistivity of Vacuum Vibrated Anodes while Maintaining High Density

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Abstract

The use of vacuum on modern compactors producing anodes for aluminum smelting has become widespread due to the increase in density and improvement in other anode properties that can be achieved. In response to EGA's Jebel Ali smelter increasing metal production in the potlines, the Carbon Plant increased anode size and retrofitted both Paste Plant compactors with vacuum. This allowed the larger anodes to be made with higher densities than previously. In the period following the retrofit, there were issues with unexpectedly high anode electrical resistivity values. This paper summarizes the work done in the Carbon Plant to regain control of anode electrical resistivity without losing the desirable increase in anode density.

Keywords: Carbon paste plant, vibrocompactor, vacuum compaction of anodes, anode electrical resistivity, anode density.

1. Introduction

Emirates Global Aluminium produced 2.6 million tons of cast metal in 2017 from two production sites - Jebel Ali, which operates 6 different cell technologies, and Al Taweelah, which operates 2 different cell technologies. The original cells at EGA were started in 1979 at Jebel Ali with the plant expanded with more modern cell technologies at regular intervals since then. The Al Taweelah site was started up in 2009 and expanded in 2013 - 2014.

To support further amperage increase at JA plant, EGA has decided in 2014 to upgrade its anode production unit to be able to produce anodes up to 1600 mm long [5]. The project included the revamping anode forming and cooling sections, anode conveyors, cleaning machines, baking furnaces height increase and adding anode slot cutting machines. The upgrade of the forming machine provided the opportunity to include the state-of-the-art features such as vacuum, top counter pressure and density control. After the retrofit the plant faced challenges in maintaining anode quality mainly in terms of anode electrical resistivity. In this article we will share what are the advantages observed and the difficulties we faced after the introduction of vacuum compaction, the investigations conducted and the process changes made to improve anode resistivity. We will also discuss the impact of anode resistivity change on performance of the reduction lines.

2. Advantages of Vacuum Compaction

2.1. Forming at High Temperature

Forming anode at higher temperature can increase anode density for a given paste quality as the fluidity of the paste allows a better compaction. But with atmospheric pressure compaction, there is a threshold forming temperature (generally between 148 to 150 °C) above which the risk of anode cracking is very high. Compacting under vacuum allows going beyond that threshold without cracks, hence allows increasing anode density. During our trials at EGA Jebel Ali, we observed a gain of density of around 0.008 g/cm^3 with an increase of forming temperature of 10 °C. (See Figure 1). After the upgrade we have increased forming temperature by 15 °C. Forming at high temperature can also help reducing the amount of water required for paste cooling providing the opportunity to explore higher mixing temperatures.

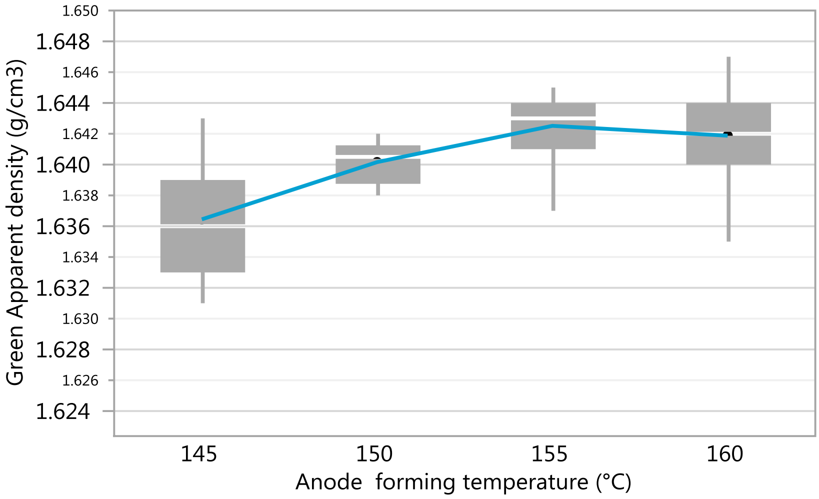

Figure 1. Green anode density and forming temperature.

2.2. Anode Density Improvement

Vibroforming under vacuum was introduced in anode manufacturing in the late 1980's. The principle was to remove air, water vapours and pitch fumes entrapped in the paste, hence reducing the porosity of the paste and increasing density.

Trials conducted at EGA have provided some more insights on the mechanism of densification by vacuum. We found that apart from the impact of forming at higher temperatures discussed above, anode formed under vacuum has higher dimensional stability after ejection. By comparing the height of the anode at the end of the compaction and after ejection, we found that anode formed without vacuum expanded by 6 mm (in height) while there was no expansion for anodes formed under vacuum. Vacuum formed anode could retain in full the density achieved during compaction, while the anode formed at atmospheric pressure shows a reduction of its apparent density by 0.015 g/cm^3 due to “swelling”. Figure 2 shows the contributions of forming temperature and dimensional changes after ejection to anode density.

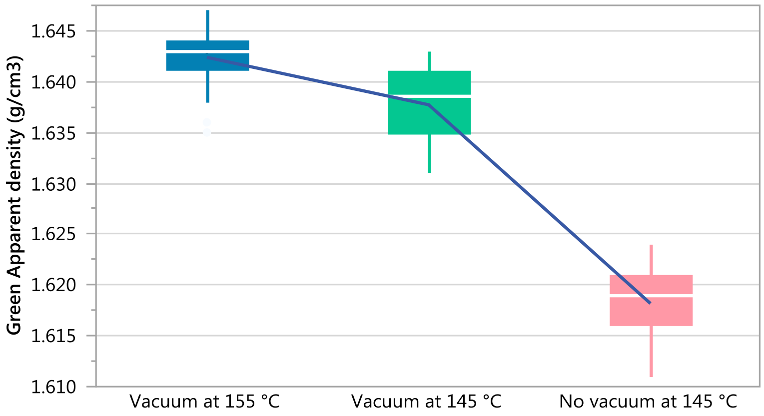

Figure 2. Effect of temperature and vacuum in anode density.

At EGA we have established a potential of density increase of 0.02 to 0.03 g/cm^3 by forming anode under vacuum, which is in line with literature references [2]. Figure 3 shows baked apparent density (BAD) and green apparent density (GAD) changes with introduction of vacuum.

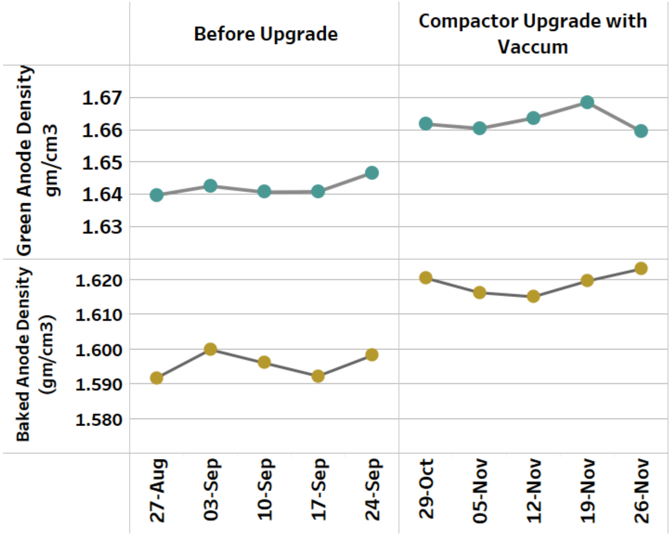

Figure 3. Impact of vacuum upgrade on BAD and GAD.

3. Challenges with Vacuum Formed Anodes

3.1. Packing Coke Sticking

By achieving higher green apparent density, vacuum compaction has also helped reducing anode pitching level for similar raw materials. But at the same time we have observed increasing trends in anode-to-anode and packing coke sticking on anodes in the baking furnaces. Anode-to-anode sticking resulted in delays in packing and unpacking operations creating conditions for more and more sticking. Further detailed analysis showed that sticking was mainly observed for anode for a particular forming line. The difference between both forming lines was the strength of vacuum applied during compaction 6 kPa (60 mbar) compared to 14 kPa (140 mbar). Anode and coke sticking was mainly observed with the forming line where vacuum was stronger.

A modification of the vacuum program and settings was done to apply similar level of vacuum for both lines and the issue of sticking was practically eliminated.

3.2. Internal Cracking and Deterioration of Anode Electrical Resistivity

In one Jebal Ali forming lines paste plant, the upgrade involved only the mould size modification and the addition of vacuum. Soon after the upgrade we observed a deterioration of anode electrical resistivity (ER). The Increase in anode resistivity was well correlated with a reduction in anode flexural strength (FS) implying presence of internal cracks. Figure 4 shows the change in anode ER and FS after the upgrade. Anode ER increased by 4 µΩm as shown in Figure 4, Visual inspection of core samples also confirmed the presence of visible cracks and micro cracks.

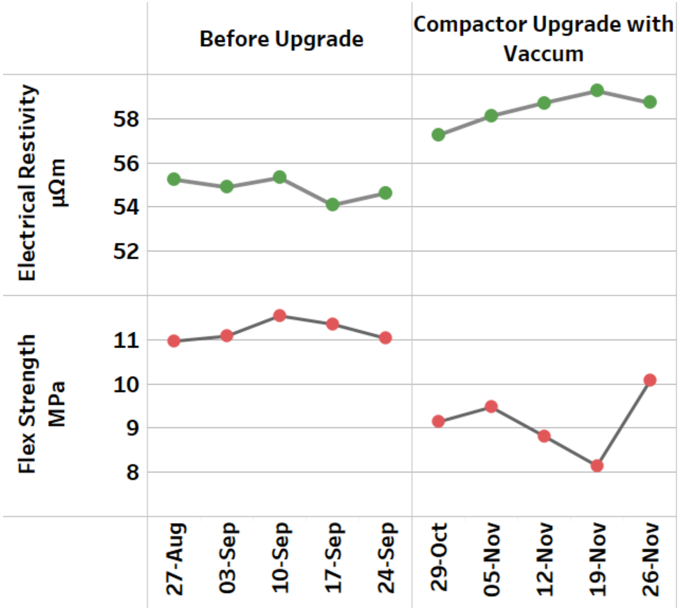

Figure 4. Change in anode ER and FS after upgrade.

Vacuum was not considered immediately as probable cause of anode cracking during baking. Our investigation primarily focused on:

- High intensity of compaction,[4]
- High heating rate of anode during baking due to relatively fast fire cycle,
- Low porosity, affecting the release of pitch volatiles during baking.[1]

Trials and data analysis were conducted to verify these potential causes.

3.2.1. Impact of Fire Cycle

To meet the required production of potlines EGA Jebel Ali baking furnaces are required to operate at relatively faster fire cycle (24 h for a design of 28 h). As result anode in some locations may have heating rates close to the maximum acceptable limit for cracking [3] (14 °C/h). To test this hypothesis the fire cycle was changed from 24 h to 27 h to assess its impact on ER and anode cracking. The results showed a marginal impact of fire cycle on electrical resistivity with an improvement of approximately 1.5 µΩm, but the variability was significantly reduced (Figure 5). Implementing the change would have led to the carbon plant not meeting pot line anode need and the short fall would have to be purchased.

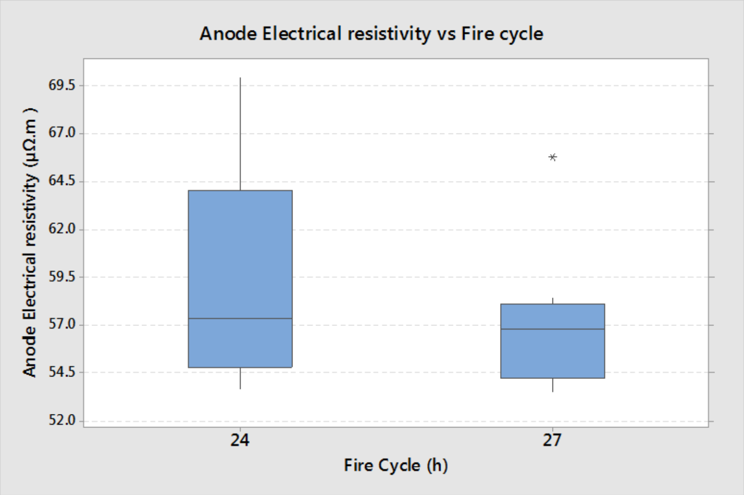

Figure 5. Impact of change in fire cycle on anode electrical resistivity.

3.2.2. Reduction of Compactor Intensity

Some of the early issues after installation of vacuum (when installed with the pre-stressed cover-weight) was turning up cover-weight pressure too high and making anodes that were difficult to bake without very severe cracking. After commissioning and fine tuning the compactor, we could achieve green apparent density of 1.670 g/cm^3 corresponding to around 1.620 g/cm^3 core density after baking. When making anodes as dense as mentioned above, there is a risk of either over-compacting anodes (generating internal cracks at the green stage) or not being able to bake them without cracks. The first action we took to try to solve the cracking issue was to reduce compaction intensity. We adjusted downwards the cover-weight pressure and the vacuum applied during compaction, which led to a significant reduction of green apparent density. But after baking those anodes, the improvement of anode electrical resistivity was marginal. (see Table 1).

We also confirmed the absence of internal cracks at green stage by taking and analyzing core samples taken from green anodes. The new settings were adopted but further reduction was limited by equipment capability and minimum density required to maintain anode shift life in pot lines.

Table 1. Effect of changing compaction parameters on BAD and ER.

Parameter	Unit	Before change	After change	Difference
Shaking pressure	kPa	350	300	- 50
Vacuum before compaction	kPa	8.5	16.8	+ 8.3
Green apparent density	g/cm^3	1.669	1.642	- 0.027
Core density	g/cm^3	1.620	1.604	- 0.016
Electrical resistivity	µΩm	61	58.8	- 2.2

3.2.3. Impact of Vacuum

As ultimate solution, the option of producing anode without vacuum was explored. A batch of anodes was produced with vacuum switched-off and baked in similar conditions as vacuum formed anodes. The results were 100 % of baked anode free of internal cracks with electrical resistivity of 55 µΩm. on average (Figure 6). But the downside was the reduction of baked anode density of about 0.025 g/cm^3. The corresponding anode weight decrease (around 20 kg) would have required a change in anode shift life leading ultimately to carbon plant not being able to fulfill the anode requirement by potlines.

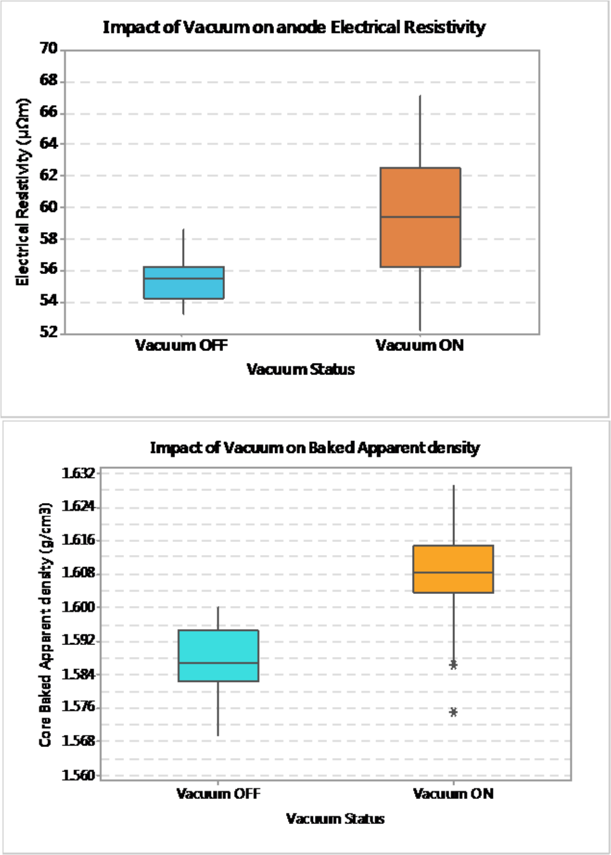

Figure 6. ER and BAD with and without vacuum.

3.3. Anode Recipe Change and Modification of Dry Aggregate

The option of switching-off the vacuum had the potential to improve anode electrical resistivity and eliminate anode internal cracking but has a significant impact on the capacity of the carbon plant to meet anode requirement of pot line. We needed to find other solutions to improve anode electrical resistivity without affecting the productivity of the plant. The idea of recipe change was to increase anode porosity and create an easy path for the release of volatiles during baking. We designed and conducted a trial of different recipes, targeting a reduction of the fines fraction in the recipe, compensated by an increase in the medium fraction. Changing the fines in the recipe impacts the particles size distribution of the dry aggregate. We used the percentage of ultrafines (particles below 32 µm) and the grain to sand ratio (GSR) to evaluate the impact of the change in the dry aggregate. Grains are particles bigger than 0.3 mm while sand represents the particles of size between 0.03 to 0.3 mm. By changing the percentage of fines from the reference to 9 % lower than the reference, the ultrafines in dry aggregate was reduced by 4 %. As sand constitutes 50 to 60 % of the fines fraction, reducing fines also resulted in reduction of the relative proportion of sand compare to grain in the dry aggregate leading to GSR increasing from 3.6 to 5.4. (Figure 7)

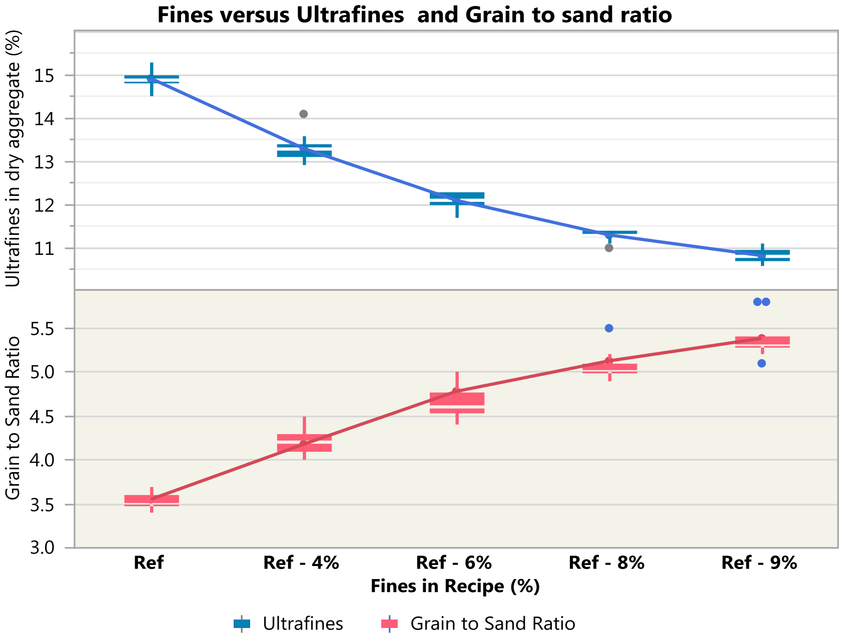

Figure 7. Impact of fines % change on ultrafines and GSR.

The results of baked anode core sample produced with different percentage of fines showed a threshold percentage beyond which the electrical resistivity of anodes of was significantly improved. Reducing fines from the reference beyond 6 % improved the average and the variability of anode electrical resistivity. Figure 8 showed impact the change in the percentage of fines on anode electrical resistivity and flexural strength.

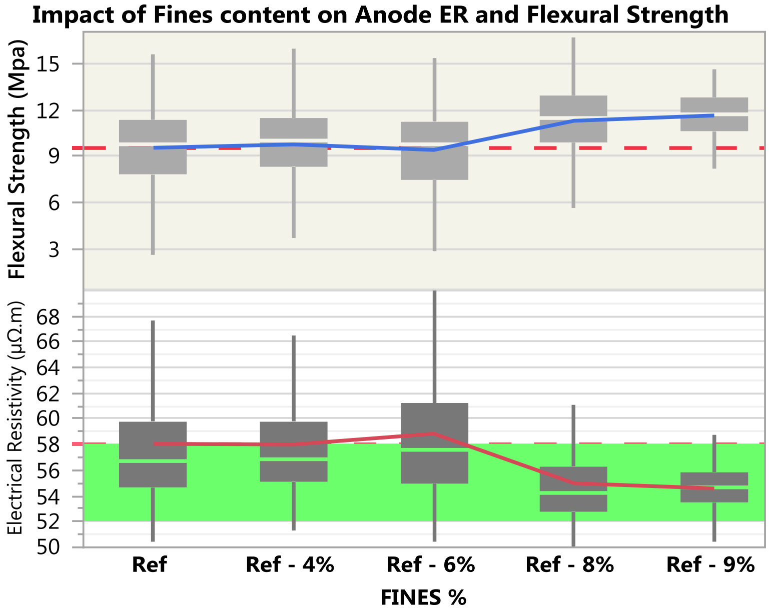

Figure 8. Improvement of anode ER with change in fines content.

Surprisingly the recipe change did not impact significantly the density or the permeability of baked anodes. Another benefit observed with the new recipe was the reduction of pitch demand as results of lower fines content.

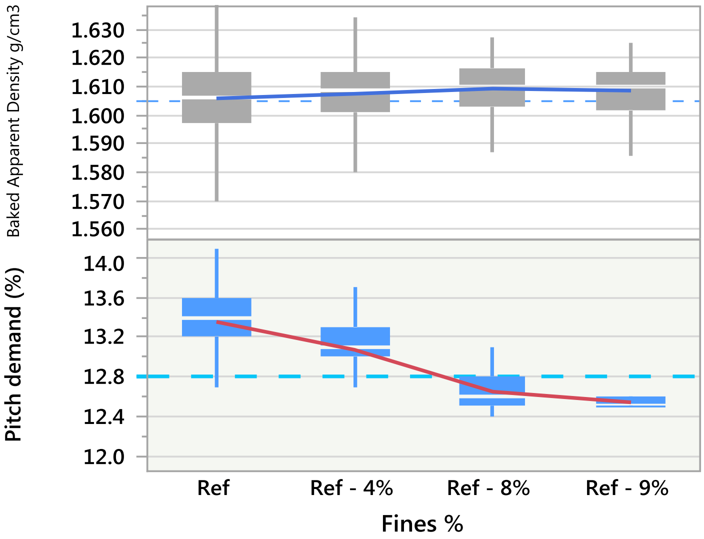

Figure 9. Baked apparent density and pitch demand vs fines content.

The mechanism of how the change in fines has improved the resistivity of anode while the density and permeability remained the same are not yet well understood. We can only formulate some hypotheses at this point:

- Reducing the fines content has also reduced the pitch demand hence reducing the amount of pitch volatiles in anodes. This can contribute to the reduction of cracking
- The change in grain to sand ratio has increase the porosity of the anodes, facilitating the releasing of pitch volatiles during baking.

The trial recipe was implemented in normal production and the improvement in anode electrical resistivity and flexural strength was sustained. The yearly average of electrical resistivity was maintained lower while achieving consistently anode baked apparent density of 1.610 g/cm^3.

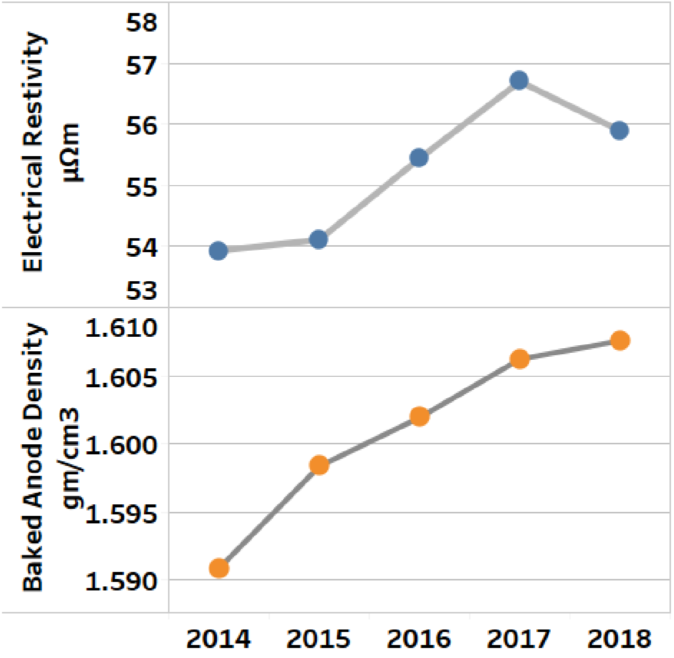

Figure 10. Yearly trends of anode ER and BAD.

4. Impact of ER on Smelter Performance

4.1. Energy Consumption

Anode voltage drop accounts for around 10 % of net cell voltage. According to modeling results anode carbon block voltage drop is in the range 250 - 310 mV for different cell technologies. Assuming that the anode resistivity at high temperature is proportional to room temperature resistivity, an increase of 4 µΩm (from 54 to 58 µΩm) in anode ER is equivalent to 19 to 23 mV increase in the net cell voltage, if anode voltage drop increase cannot be compensated by squeezing of anode-cathode distance (ACD) which can lead to other negative consequences. At energy price 50 USD/DCMWh and current efficiency 92 - 94%, such increase in net cell voltage leads to an increase in the metal production cost by 2.9 to 3.7 USD/t Al. For a company of the EGA size, the impact can be 7.25 to 9.25 MUSD per year.

4.2. High Anode Electrical Resistivity and Anode Problems

In most modern cells, the continuous thrive to increase the reduction cells size, line amperage and anode dimensions, while aiming for low energy consumption, has led to operating the cell at low ACD and low electrolyte volume. Under these conditions, variations in anode quality such as increasing of anode electrical resistivity become more critical in maintaining the stability of cell operation. This can lead to operating cells with low ("squeezed") ACD. Thus, a shift in cell thermal equilibrium could occur [6], leading to high magnetohydrodynamic (MHD) instability. Operating conditions of unbalanced anode current distribution would lead to different anode problems such as spike formation and excessive dusting. The increase in anode problems will results in losses in cell current efficiency. Also anodes with internal cracks are prone to vertical and horizontal splits in the cell.

The graph in Figure 11 shows some correlation between high anode electrical resistivity and anode problems.

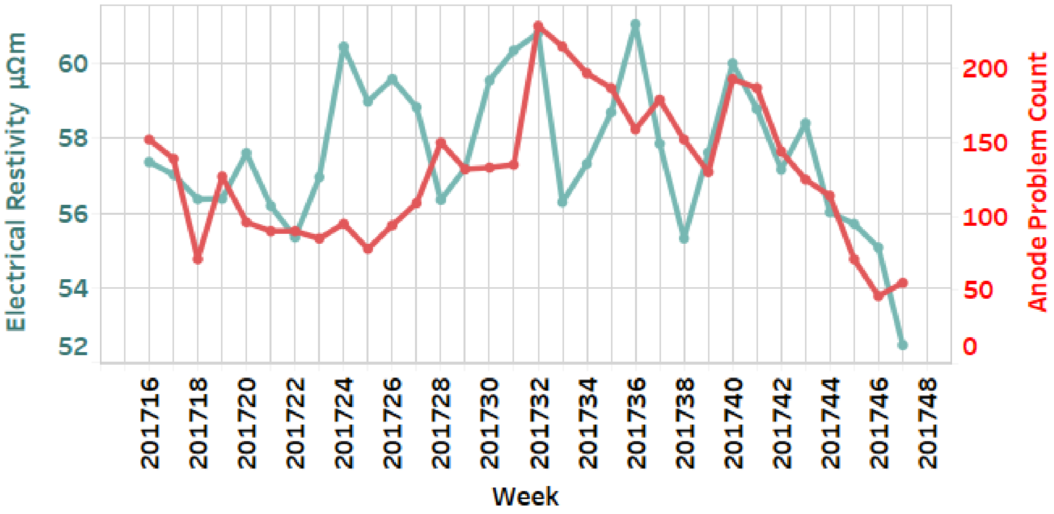

Figure 3.

5. Conclusions

The introduction of vacuum forming has contributed to an increase in anode density and a decrease of anode air permeability. The improvement in air permeability lowers anode consumption while the increase in density supports amperage increase in potlines.

However, vacuum formed anodes have also shown higher electrical resistivity due internal cracking during baking. The deterioration of anode electrical resistivity has led to higher instability in cell operation and a significant increase in anode problems, impacting overall plant performance. To improve anode electrical resistivity while retaining the density improvement, EGA had to find process adaptations other than switching off the vacuum. Several trials were conducted focusing on recipe changes, mainly on reducing percentage of fines fractions in the recipe. The results of the trials showed that a reduction of fines by 9 % from the reference recipe lowered significantly the anode resistivity. After full scale implementation of the best trial recipe, the objective of reducing anode resistivity while maintaining higher anode density was achieved.

These results demonstrate the importance of using extensive data analysis, plant trials and design of experiments to investigate deviations and improve the process and the quality.

6. References

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