Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

Maximizing Green Anode Slots Height through a Rigorous Methodology and Finite Elements Modeling

Jean-Louis Abeille[1], Patrick Sornin[1], Yann El Ghaoui[1], Philippe Contard[1]
Alexandre Gagnon[2]
François Moralès[3]
Marc Gagnon[4]
Franck Fruleux[5]

1: Rio Tinto Alcan - Aluval - 725, rue Aristide Bergès - BP 7, 38341 Voreppe Cedex, France
2: Rio Tinto Alcan Arvida Research and Development Centre, 1955 blvd Mellon, Jonquière, Québec, G7S 4K8, Canada
3 : Rio Tinto Alcan, LRF, Saint-Jean-de-Maurienne, 73300, France
4: Aluminerie Alouette Inc. 400, chemin de la Pointe-Noire, P.O. Box 1650, G4R 5M9, Canada
5: ECL™, 100 rue Chalant - 59790 RONCHIN, France

Keywords: Anode slots, specific consumption, voltage drop

Abstract

Anode slots benefits are maximized when they are high enough to last the entire anode service life: around 450 mm height for the AP30 technology. The most cost effective method for making slots is to form them at the green stage, directly in the vibrocompactor or press. However, plants struggle to form slots higher than 300 mm due to cracks and segregation in the anode. The alternative is to saw the slot in the baked anode but it is CAPEX and OPEX intensive. The challenge has been taken by RTA and Alouette Smelter to form 400mm high slots. Each step of the anode manufacturing and handling process was reviewed through an in-depth risk analysis, teaming up finite elements modeling specialists with process, production and equipment manufacturing experts. Technical solutions were found to increase the height of the slots and to ensure a low scrap rate through new slot design and adaptations to the existing transport and handling equipment.

Introduction

Anodes slots have been widely implemented in the last 15 years across all aluminium smelters. The main purpose of anodes slots is to reduce the coverage of the insulating CO_2 bubble layer between the electrolytic bath and bottom of the anode. The alumina reduction generates CO_2 gas which forms an insulating layer due to bubble coalescence under the carbon anode. The slots facilitate enhanced gas release as they reduce the mean free path of the bubbles. For an AP30 technology, typical slotting is shown on figure 1.

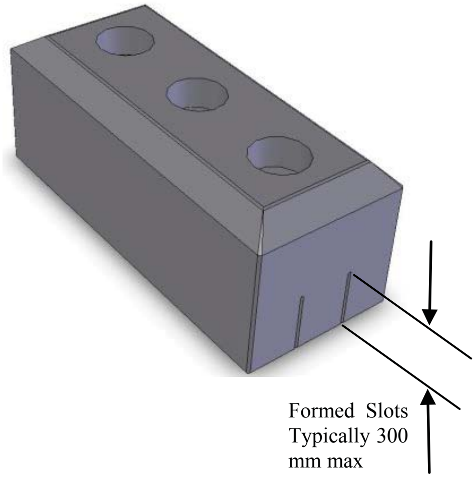

Figure 1 – Typical AP30 slotted anode.

There are two slots per anode block in the longitudinal direction. For AP30 technology and according to different parameters such as amperage, Anode Cathode Distance (ACD) and bath chemistry, an increase of 10 mm in slot height reduces the bubbles over voltage by about 1 to 3 mV. This voltage drop saving results in increased ACD which can be valorized through a combination of increased current efficiency, reduced specific energy consumption and amperage increase depending on the pot operating window and facilities constraints. The ideal slot geometry is:

- High enough to last the entire anode cycle (about 450 mm height for an AP30 anode)
- Wide and clean enough to allow bubbles to escape quickly and enhance bath flow in the ACD (about 10 to 15 mm width)
- Enhances bath flow and turbulence in the center channel to facilitate alumina dissolution and distribution

Anodes slots have some drawbacks and constraints associated with:

- Less available carbon under pin
- Increased Anode fragility
- Increased surface area for anodes susceptible to air burn
- Dusting problems catalysis [1]
- Other concerns related to the way slots are achieved, detailed in the next section

Existing solutions to slotting anodes: form slots at the green stage or saw baked anodes

A cost effective solution to slot anodes is forming the slots at the green stage. The CAPEX involved is usually small as the equipment modifications are limited to vibroformer or press mold modifications: blades are added inside the mold. Some smelters however have also to invest in a slot cleaning machine to remove the remaining packing coke after baking. The concerns with this green anode slot forming technology are the following:

- As the mold is generally divided in three compartments, the anode is more susceptible to segregation and density variation
- Slot elevation is generally limited to about half the anode height due to the increased risk of cracks forming during handling and storage in the green stage [2]
- Packing coke may agglomerate and stick inside the slots and contribute to increased carbon in the bath

The strengths of this slot forming technology are the following:

- Low-implementation and maintenance cost
- 100% of anodes are slotted
- No recycle of carbon due to slot cutting

Another existing solution to slot the anodes is to saw after baking. There are several suppliers that propose mainly circular saws. The concerns and constraints with this technology are the following:

- High cost of implementation (CAPEX)
- Cost of saw maintenance (OPEX) mainly linked to blades replacement
- Very high OEE or redundancy needed to slot 100% of the anodes
- Carbon saw dust recycling
- HSE hazards to be addressed (noise, dust, automatic machine guarding)

The strengths of this technology are the following:

- It allows production of tall and clean slots, without any impact on anode homogeneity as anodes are formed without any compartments in the mold

Techno-economic sensitivity study

The state of the art today across RTA smelters for AP30 technology is 300 mm high slots formed in the green stage. The alternative is sawing baked anodes around 400 mm high, which is currently the maximum height proposed by saw manufacturers. A sensitivity analysis according to different parameters was carried out to compare both options and check if it was better to go for 400 mm slots with a sawing technology. The following hypotheses were taken for the study:

Constants:

- 400 kt/y Al AP40 smelter
- Cost of sawing: CAPEX 15 $/t, OPEX 2.5 $/t
- WACC (Weighted Average Cost of Capital) 8%
- +100 mm of slots (from 300 mm at green stage to 400 mm achieved by sawing) equivalent to - 30 mV of voltage drop saving

Variables:

- Metal margin

How voltage drop saving is valorized: energy saving or extra metal production: - 30 mV is equivalent to - 90 kWh/t or 0.8% of production increase.

Result:

- Incremental Net present value (NPV) over 5 years

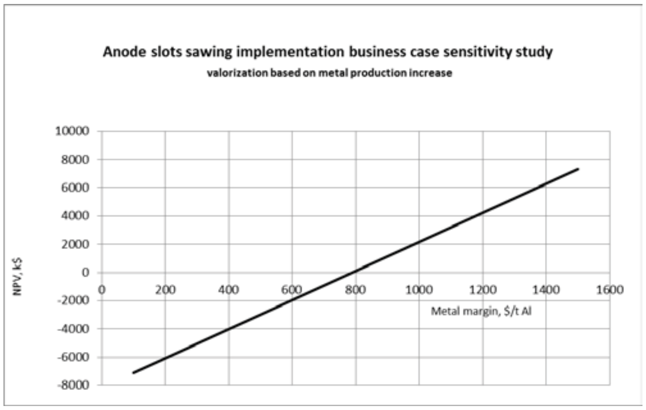

Figure 2 – Slot sawing value creation (5 years NPV)

The break-even point to saw slots is around a margin on metal of 800 $/t (cf. Figure 2). This high level study shows that it is difficult to justify such an investment, even more today when aluminium price suffers strong pressure and most of the smelters have limited cash to invest.

RTA Technology decided to explore how to increase the slots in the green stage in order to get the benefits of higher slots without the higher cost of sawing. The target to reach at least 400 mm was set.

The taller green slots alternative

Taller green slots offer a low CAPEX/OPEX solution, but with 3 main technical challenges to address:

1. Anode homogeneity
2. Slot cleanliness
3. Mechanical behavior and integrity during handling

For the first two challenges, technical solutions are already known and available. At the vibroformer step, especially with a bottom blade in the mold, paste distribution is a key point. To ensure appropriate paste distribution in the mold, there are two main drivers related to the transfer hopper. First of all paste must be well distributed in the hopper and then the helmet valve must have a fast opening action.

Various equipment for cleaning the slots after baking are available, the most efficient are mounted with retractable blades and compressed air jets.

Most of the time, mechanical integrity is addressed by a trial and error process, which consumes time and money without good chances of finding the optimum solution. To maximize the opportunity of finding the optimum slot design and avoiding iterations, the best way is to use Finite Elements Modeling (FEM). However, there are two key drivers to obtain meaningful results.

First of all, a good characterization of the material and then a good assessment of the maximum forces applied to the anode.

Methodology

The methodology applied for optimizing the green anode slot height is split into four steps:

1. Site data collection
2. Green anode material characterization
3. Appropriate model design
4. Best slot design definition

The first step is a study of the mechanical handling of the anodes, all the way through the carbon plant. The aim is to assess all the handling constraints through the whole circuit to identify the highest stress conditions for the green anode blocks. In general, the main handling constraints are due to cranes or storage. The Furnace Tending Assembly (FTA) grab must be considered in detail as well as the stacking crane grabs and anodes storage in case of pyramidal storage. In addition to those points, all conveyors, turnover and end stop devices must be checked and adapted to avoid shock loading that might crack or break the anodes.
As the Grain on Sand (G/S) ratio has a determining influence on anode resistance to cracking [3], if plant has a low G/S ratio, a paste plant audit should be conducted in order to establish which modifications should be applied to increase the G/S ratio to 5.

The second step is the green material characterization realized through lab tests on a representative batch of green anodes core samples. Those tests determine the Ultimate Tensile Strength (UTS) to be used in the modeling phase.

The third step is the design of the FEM taking into account the maximum forces applied to the anode. As well as the material characterization, special care should be taken to characterize the forces applied and their application points.

The last step is the slot design optimization, through the assessment of several alternative designs. As the FEM allows testing of many options, the optimization can be tailored to match the investment steps until reaching the full potential of the concept. As the study has enabled identification of the highest applied stress devices for anode block handling, bottleneck equipment can be modified in order to reduce mechanical stress on the anode, allowing the realization of deeper slots. In fact each equipment modification has a cost to balance with the deeper slot benefit. The basic scenario involves the assessment of the highest slot possible without modification other than the blades. Then several scenarios can be considered depending on the investment cost and the pay-back speed linked to the economic conditions.

The methodology described above has been proposed and applied at the Alouette Smelter, in the framework of joint technological development, with the objective of reaching 400 mm high slots. The first FEM model has been developed and tested for this project.

Model development

One of the challenges in developing a predictive model was to properly characterize the mechanical properties of the green anodes. For this purpose, core sample from green anodes have been taken and several lab tests done. The Arvida Research and Development Centre conducted the following lab tests:

- Three point bending test
- Compression test
- Shear test

Those data have been used for model calibration and material characterization. Core samples have been modeled in the testing machines by FEM and load cases reproduced in order to calibrate the model.
To speed up the development process, the first green anodes core samples have been taken from the Alma smelter followed by other batches of Alouette smelter green anodes. This approach also enlarged the sample size and improved the reliability of the model calibration. Those lab tests permitted validation of the model on simple shape under well controlled conditions.

Lab tests have defined the maximum tensile stress acceptable for Alouette green anode material. As green anode is a friable material not able to accept plastic deformation, we have utilized the lower values of the batch in the models. Furthermore, a green anode is a non-homogeneous material composed from aggregates, plus a binding agent. For this reason we have retained a safety coefficient, as generally applied for this kind of fragile material. Finally we characterized an acceptable value for the UTS.

Figure 3 – Batch of green anodes core sample after destructive laboratory tests

Additional tests on a complete green anode and on drilled cores samples (cf. Figure 3) have also provided information about the green anode material failure modes. Those tests in addition to the ones realized with classic cores sample, have allowed the model to assess more complex geometries.

At the Alouette smelter, site data collection has identified that the highest mechanical loadings are generated by the FTA grab. A 3D model of the anode has been developed (cf. Figure 4), including the load application points generated by the grab. It has been the basis of the FEM with a detailed mesh around the stress concentration areas.

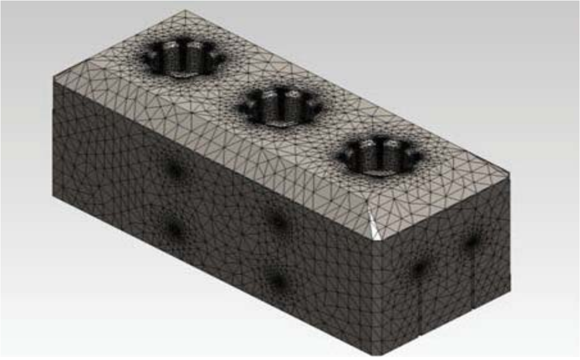

Figure 4 – 3D Finite element mesh of anode handled with the FTA grab.

This FEM model allows assessment of the anode mechanical behavior under different loading cases by visualizing the high stress zones and distortions (cf. Figures 5 and 6). We can observe that a compressive force applied on the longitudinal face of the anode may generate a crack at the stub-hole.

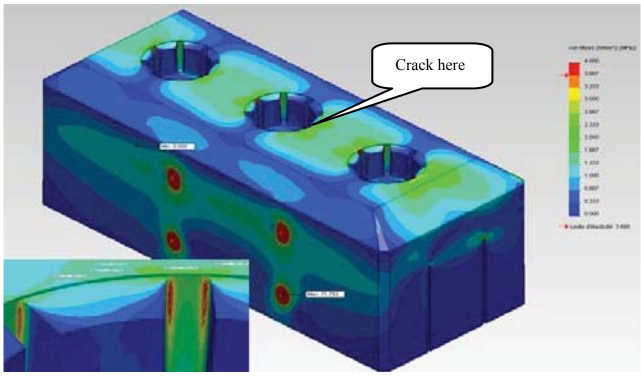

Figure 5 – Visualization of high stress areas and assessment of maximum values

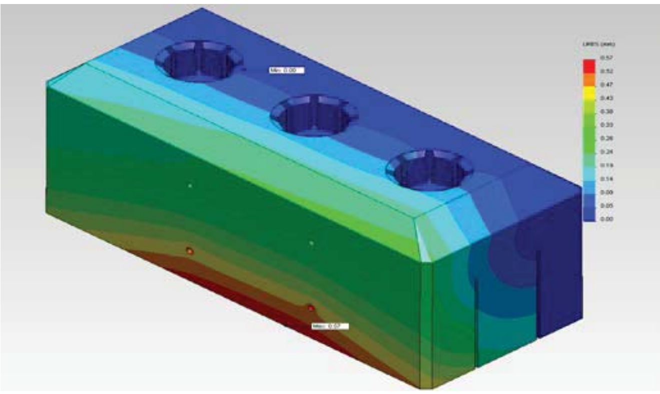

Figure 6 – Visualization and assessment of anode distortions

Implementation

As mentioned previously this methodology allows examination of several alternatives to achieve the best techno-economic benefit. This approach also permits confirming modeling results step by step, so the implementation phase has been split into two trial steps:

- Phase 1: Increase the current slots height to maximum potential with no investment cost
- Phase 2: Reach the full potential of molded slots up to 400 mm or beyond, challenging slot shape, handling, conveying, etc.

Modeling phase has permitted identification of the optimum for both cases.

The theoretical maximum slots heights for the Alouette smelter are:

- Phase 1 – After harmonization of FTA grabs clamping forces, maximum slots height should be 340 mm for a benefit estimated at 12 mV compared with the current 300 mm slots.
- Phase 2 – New slots shapes with modification of requested handling equipment: maximum slots height should reach up to 420 mm.

For the phase 1, the first step of trial implementation phase started in August 2013, with the production of 160 anodes with 340 mm slots. One of the vibroformers molds has been equipped with 340 mm blades. The trial batch has been passed through the entire green anodes handling circuit without any trouble, no cracks or breakage has been recorded from the vibroformer to the ABF loading. Those practical results have confirmed the FEM model calibration.

After the normal baking process, the trial batch was unloaded without any anodes breakage or cracking. No further trouble was recorded at the anode rodding stage.

Anode batch was tested in the pots in September and October 2013 without observing any more trouble than the 300mm slotted anodes.

The next step for the end 2013 is the realization of a large trial batch of about 2000 anodes in order to evaluate the full pot performance benefit on a representative scale.

For the phase 2, the scope of technical modifications has been expanded to include more freedom on slot design, handling and conveying. A first step has been to optimize the FTA grab to minimize mechanical overloading. This study has been done closely with ECL to optimize the handling tools. The second step, with the help of modeling, has been to design several slots and test the anode mechanical resistance with the FTA optimized grab. A short list of slots shapes was selected that offered the possibility to reach up to 420 mm height in the typical Alouette case. In parallel to the mechanical modifications, the G/S ratio will be progressively increased beyond 5, through minor paste plant modifications and a thorough evaluation of the grain size distribution parameter. The next step will be the implementation of a small trial batch with slots height around 400 mm. It will allow further calibration of the FEM model and consequently will further increase the project value for the smelter. The CAPEX to generalize the second phase has already been estimated and it is significantly lower than a sawing facility.

Financial benefits

Assuming the same hypothesis taken in the sensitivity study, 340 mm slots formed at green stage were compared to 400 mm slots sawed after baking.
Constants:

- 400 kt/y AP40 smelter
- Cost of sawing: CAPEX $15/t, OPEX $2.5/t
- Cost of forming slots at green stage : $0/t
- WACC 8%
- Green stage: 340 mm slots allow an increase in production of 0.3% (compared to 300 mm)
- Sawing: 400 mm slots allow an increase in production of 0.8% (compared to 300 mm)

Variables:

- Metal margin

Result:

- Net present value over 5 years

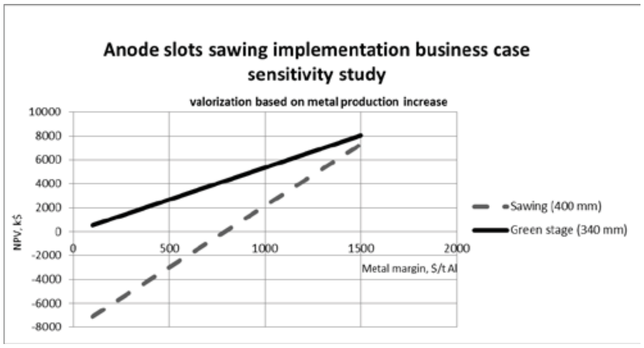

Figure 7 – Slot sawing value creation vs. green stage slots (5 years NPV)

On a 5 years time span, it is creating more value to increase the green slots to 340 mm instead of investing in a sawing machine producing 400 mm high slots (cf. Figure 7).

Conclusion

The results achieved in Alouette encourage implementation of the taller green slots as it is a really convenient alternative to sawing. Firstly, a quick win was identified by elevating the slot from 300 to 340 mm height with no heavy investment. Secondly, there are technical solutions to go higher, with limited CAPEX. FEM was demonstrated as a powerful tool to support this design optimization instead of a costly and time consuming trial-and-error method.

References:

[1] Production and performance of slotted anodes, Markus W. Meier, Raymond C. Perruchoud and Werner K. Fischer, Light Metals 2007
[2] Slot cutting in anodes, Jean-Jacques Grunspan, Light Metals 2007
[3] An approach for a complete evaluation of resistance of a material to thermal shock, Bernard Samanos, Christian Dreyer, Light Metals 2007