Anode Issues during Smelter Capacity Creep

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Abstract

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Most of the smelters have gone through capacity creep thanks to increased current intensity. The potlines creep has been achieved gradually by multiple changes of the cell components and by improvements of the process control and practices. In case of the high amperage (300kA) potlines installed in the nineties, the progressive creep of current has reached the 360 kA level.

Recently performed thermal-electrical (TE) and magneto-hydrodynamic (MHD) computations implementing new busbar optimizations showed possible current increase from 360 kA to 410 kA. Experiences during the last twenty years with current increase in high amperage potlines have shown that anode properties have an impact on the thermal equilibrium as well as on the magnetic stability (noise level) of the cells.

The additional anode demand from existing carbon plants leads to higher throughput in the paste plant and lower fire cycle time in the baking furnace and therefore to a deterioration of anode properties and variations.

With TE and MHD computation, the influence of variable anode quality on the cell performance has been assessed. Based on these results, targets for anode quality variations (benchmark anodes) for high amperage cells have been defined.

Solutions for the production of benchmark anodes in the existing carbon plant are described. Substantial investments for paste plant and baking furnace modifications have to be expected. To avoid these investments, the purchase of merchant benchmark anodes is a real and safe alternative to bridge the additional anode demand.

Prior to any smelter modifications, however, a feasibility study should be executed to investigate the optimal solution for cell design and its impact on anode quality and anode requirement.

Introduction

In the mid-nineties, state-of-the-art potlines (Figure 1) achieved a line current level of 300 kA [1]. These new and large smelters were located in areas where electrical energy was abundant and cheap. In order to improve the profitability, most of the smelters focused on higher amperage.

Figure 1: AP30 Cells in St-Jean-de-Maurienne

Higher profitability can be reached in an existing potline (Table 1) by:

- More metal produced
- Lower specific energy consumption
- Higher current efficiency

Smelter 600'000 tAl/year			
Technical		Financial	
Line current	360'000 A	LME Al price	2'000 $/tAl
Current efficiency	94.5 %	Production cost	1'500 $/tAl
Energy consumption	12.9 MWh/tAl	Energy price	20 $/MWh
Pot voltage	4.1 V	Al_2O_3 price	350 $/t

Table 1: Technical and financial facts of an existing potline

The possible earnings by changing smelter production parameters are shown in Table 2. Maximal earnings depend on local cost for material, energy and capital. The financial optimum must be defined individually for every smelter.

Influence of production parameters on earnings		
Parameter	Change	Earnings in $/year
Production	+ 10'000 tAl/year	+ 5.0 Mio
Current efficiency	+ 1 %	+ 7.8 Mio
Energy consumption	- 0.5 MWh/tAl	+ 6.0 Mio

Table 2: Earnings by changed production parameters

The progressive creep of current has reached in less than two decades the impressive level of more than 20%, e.g. from 300 kA to 360 kA in our case study.

Increasing the line current by unchanged current efficiency would lead, by a constant level of the cell ohmic resistance, to higher cell voltage and to increased energy consumption (Table 3).

Interdependance between line current, pot voltage and energy consumption by constant ohmic pot resistance			
Line current	kA	**300**	**360**
Pot voltage	V	4.1	4.6
Energy consumption	kWh/kgAl	12.9	14.5
Current efficiency	%	94.7	94.7

Table 3: Theoretical effect of current increase on cell voltage and energy consumption

To avoid overheated cells most of the efforts have been made to keep the internal heat (heat generated by the current passing from the anode to the end of the cathode collector bars) under control. This means decreasing the bath resistance by lower anode cathode distance (ACD), or by lower bath resistivity and compensating the higher cell voltage by design and material improvements [2]. The list below shows the major actions taken for maintaining or improving the current efficiency and energy consumption.

- Strict control of high AlF_3 and low Al_2O_3 content
- Zero anode effect
- Longer, slotted anodes
- Precise anode setting
- Improved magneto-hydrodynamic behavior
- Reduced cell voltage by lowering anode cathode distance (ACD) graphitic cathode blocks and collector bar design [3]
- SiC side wall blocks

Further increase of current from 360 kA to 410 kA can be achieved by:

- Improved cathodic current distribution by cathode bar design
- Shaped cathode surface [3]
- Longer anodes
- Optimized busbars design [4] [5]
- Decrease of cell voltage (internal heat)
- Improved anode quality

The thermal-electrical and magneto-hydrodynamic computation of the cell is of course a mandatory tool for the verification of the technical solutions planned to increase the current.

Cell performance

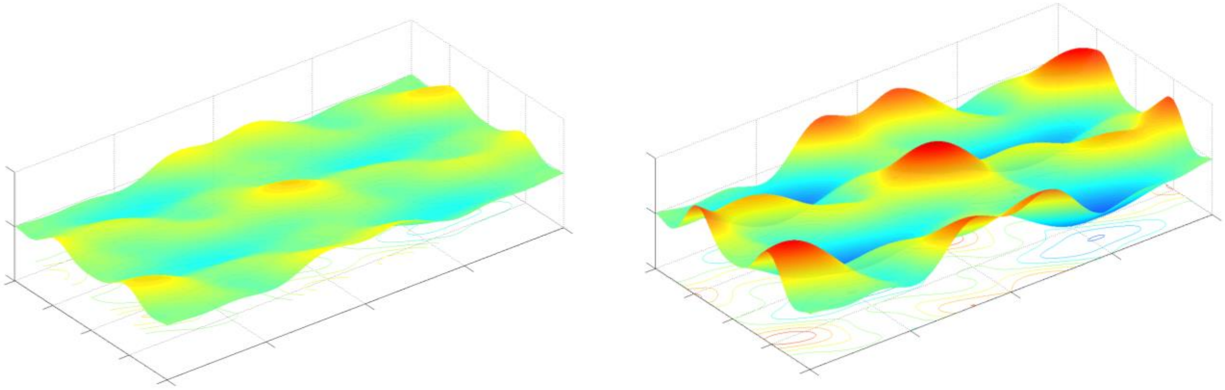
A series of full TE and MHD computations have been performed using the MONA [6] software and the model of a generic reduction cell. The effect of variable anode quality (Table 4) on the cell performance has been assessed. Based on these results, the potential and the limitations for current increase by changing anode properties and variation can be outlined. The impact of the anodes on the current distribution, from the anode setting to the butts removal, has also to be quantified.

Anode parameters	Unit	Range
Baked apparent density	kg/dm^3	1.50 – 1.64
Specific electrical resistance	μΩm	46 - 60
Thermal conductivity	W/mK	3 - 5
Butt cross section	%	60 - 100

Table 4: Anode quality variations used in the computation model

The anode properties used for the computation and their variability depend on the raw materials, but also on the manufacture process. For the calculation of cells with standard busbars at 360 kA constant anode properties corresponding to the actual values and variation were considered. For the calculation of cells with optimized busbars at currents ranging from 360 to 410 kA, anodes randomly distributed in the cell, with properties covering the range shown in Table 4 were used as inputs in the model.

The **Noise Factor** quantifies the ability of the cell to tolerate variations before becoming unstable. A high noise factor means that waves at the metal-bath interface are damped more slowly or even are being amplified. This is illustrated in Figure 2.



Low Noise Factor

High Noise Factor

Figure 2: Metal bath interface (noise level) influenced by anode quality

High noise factors are an indication of thermal-electrical and magneto-hydrodynamic instability of the cells and leads to increased specific energy consumption and lower current efficiency.

Anode performance

The variability of anode properties influences the cell stability by:

- Non uniform anode current distribution
- Disturbed cell thermal equilibrium
- Carbon dust in the bath

The ANODE APPARENT DENSITY values used in the computation model show current variations higher than 25% between light and heavy anodes in the same cell (Figure 3). A non-uniform anode current distribution causes horizontal currents in the metal which affects the MHD state of the cell (noise). Disturbed anode current distribution lowers the current efficiency. An empirical model predicts that a 10% standard deviation of the anode current distribution diminishes the current efficiency by 0.6% [7].

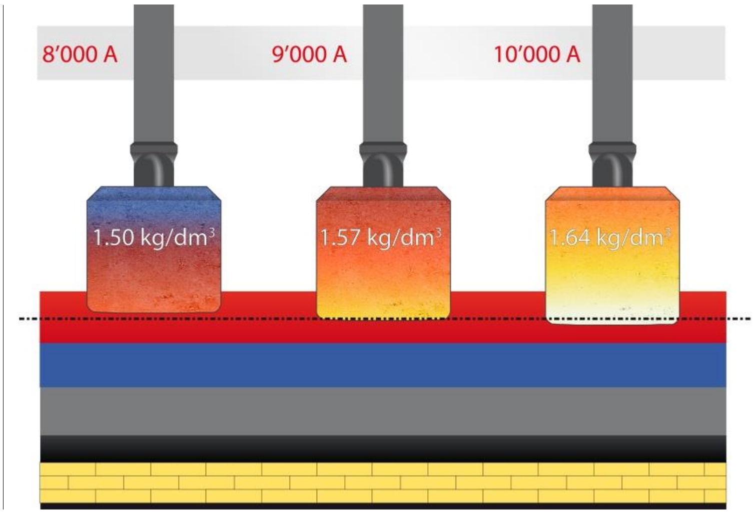


Figure 3 Influence of anode apparent density on anode current

The RESIDUAL SECTION OF BUTTS has a significant influence on the anode current distribution. Anodes with poor CO_2, air reactivity and permeability lead to reduced butt size [8] and therefore to low anode current especially during the second half of the anode cycle (Figure 4).

The net carbon consumption [9] increases proportional to the decreasing butt weight.

Anodes with bad reactivity behavior are responsible for carbon dust formation in the cell.

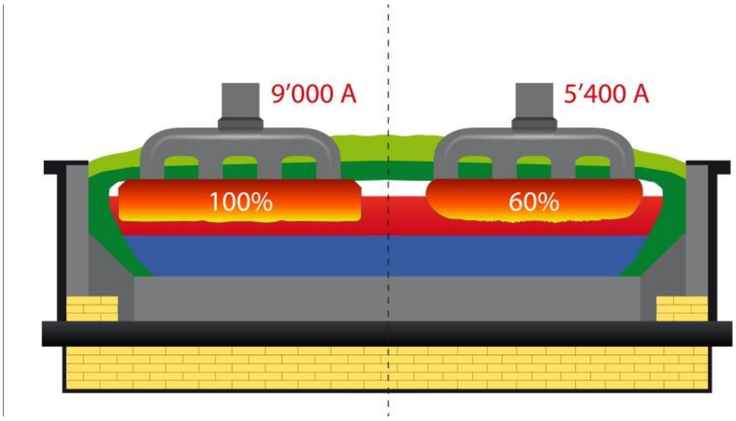


Figure 4: Influence of residual butt section on anode current

Disturbed anode current distribution due to variations in apparent density and anode reactivity is a limiting factor for current creep.

Mean value and variations of the SPECIFIC ELECTRICAL RESISTANCE and the THERMAL CONDUCTIVITY of the anodes influence the thermal equilibrium of the cell. These properties depend on the anode temperature. With higher temperature, the specific electrical resistance decreases, while the thermal conductivity increases (Figure 5).

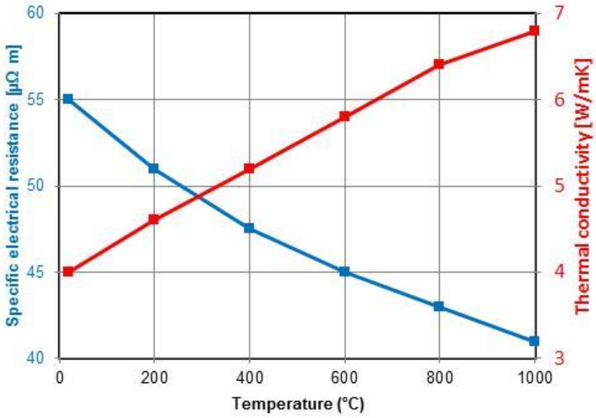


Figure 5: Relationship between anode properties and temperature

The influence of temperature on the anode properties during the anode lifetime in the cell has been considered for the computation of the thermal equilibrium of the cell. Mean values and variations of these properties affect the anode top temperature and changes the heat losses of the cell and hence the thermal equilibrium (bath temperature) of the cells. Higher temperature on the anode top leads to airburn and carbon dust formation.

Excessive CARBON DUST in bath (Figure 6) is initiated by anode quality issues (selective burning) and leads to the following problems [10] usually ending up with a vicious circle:

- Increased bath resistance (+ 0.2% C in bath results in + 5% of the bath resistance)
- Squeezed anode-cathode distance (ACD)
- Formation of anode spikes
- Higher bath temperature
- Lower current efficiency (up to - 3% CE)

Figure 6: Carbon dust in the cell

Benchmark anode quality

The influence of anode properties variations on the cell performance (noise factor) has been assessed by thermal-electrical and magneto-hydrodynamic computations that show the increased sensitivity of the cells with high anode current density. Practical experience with excessive carbon dust formation in cells with increased line current [11] is also considered.

For cells with an anode current density above 0.9 A/cm^2, mean values and variations of BENCHMARK anode properties are defined in table 5.

BENCHMARK anode properties	**Unit**	**Mean**	**Max 2 STD**
Baked apparent density	kg/dm^3	min. 1.58	0.015
Specific electrical resistance	µΩm	max. 54	3
Thermal conductivity	W/mK	4	0.4
Air permeability	nPm	max. 0.6	0.4
Air reactivity residue	%	min. 85	4
Air reactivity dust	%	max. 3	2
CO_2 reactivity residue	%	min. 90	3
CO_2 reactivity dust	%	max. 2	2
Phosphorus	ppm	max. 10	

Table 5: Benchmark anode properties

Benchmark anodes can only be produced with petroleum coke with high and steady bulk density, low and constant specific electrical resistance and low CO_2 and air reactivity losses [12].

Anode and raw material properties must be measured and monitored on a routine basis to avoid deviations leading to unstable cell operations.

Anode production

Table 6 shows the baked anode requirement, anode weight, length, height (width 650 mm) and the anode current density by increasing line current from 300 kA to 410 kA in an existing smelter.

Anode requirement	**Unit**	**Start-up**	**Actual**	**Future**
Line current	kA	**300**	**360**	**410**
Al production	t/year	500'000	600'000	680'000
Baked anodes requirement	t/year	280'000	335'000	380'000
Baked anode weight	kg	870	980	1'070
Baked anode height	mm	600	625	650
Baked anode length	mm	1'450	1'550	1'650
Anode current density	A/cm^2	0.796	0.893	0.956

Table 6: Baked anode requirement

GREEN PASTE production has to be increased from 315'000 to 420'000 t/year. With a production uptime of 18 shifts/week, 49 weeks/year and an unchanged availability of 80%, the green mill line throughput increases from 28 to 36 t/hour (Table 7). The specific mixing energy, influencing the physical anode properties as apparent density, mechanical strength and permeability decreases from 10 to 7.8 kWh/t anodes.

Paste plant	**Unit**	**Start-up**	**Actual**	**Future**
Line current	kA	**300**	**360**	**410**
Green paste production	t/year	315’000	375’000	420’000
Green anode weight	kg	915	1’030	1’120
Green mill throughput	t/h	2 x 28	2 x 33	2 x 36
Specific mixing energy	kWh/t	**10**	**8.5**	**7.8**

Table 7: Green mill operation parameters

A significant production increase of green and baked anodes, without significant changes in equipment and process parameters, has a deleterious influence on anode properties mean values and variations (Figure 7).

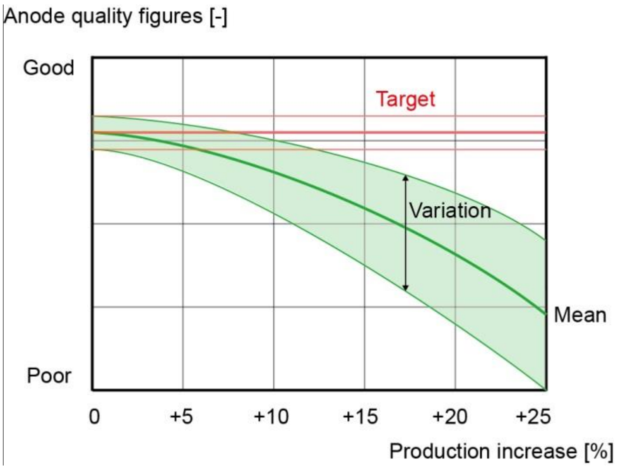


Figure 7: Interdependence between anode quality and production increase

To produce target quality green anodes, the following bottlenecks must be eliminated.

- Ball mill production capacity
- Preheating of dry aggregate
- Insufficient specific mixing energy
- Paste cooler capacity
- Vibroformer availability and process control
- Green anode cooling capacity

The estimated cost of these corrections is 20 to 30 million USD, the downtime of the paste plant will be between two to three months. After the paste plant refurbishment, the optimal process parameters must be defined.

Such an investment only makes sense if the capacity of the baking furnaces can cope with the increased green anode production without significant decrease in baked anode properties.

BAKED ANODE requirement is increasing from 280’000 to 380’000 t/year (Table 8).

Baking Furnace	**Unit**	**Start-up**	**Actual**	**Future 6 fires**	**Future 7 fires**
Line current	kA	**300**	**360**	**410**	
Baked anodes requirement	t/year	280’000	335’000	380’000	380’000
Production per fire and year	t	46’700	55’800	63’300	54’300
Tons per section	t	167	188	180	180
Fire cycle time	h	31.4	29.5	24.9	29
Total heat up time	h	**188**	**177**	**149**	**174**

Table 8: Baking furnace operation parameters

In the two baking furnaces with three fires each, a crane places three rows of vertically bundled anodes into the pits (Figure 9). Through the increased anode length from 1’450 to 1’650 mm, the anode pile reaches the flue wall height as shown in Figure 8.

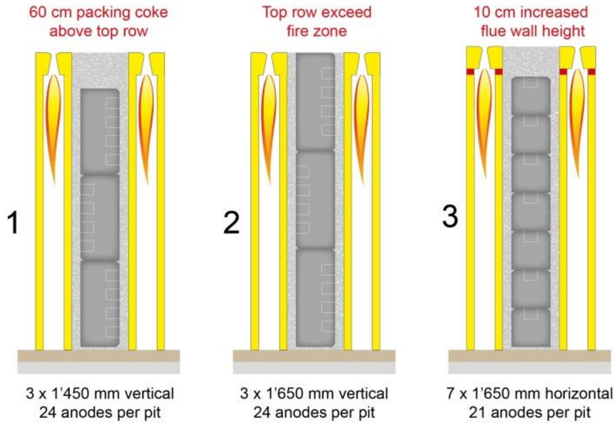


Figure 8: Anode arrangement in pit

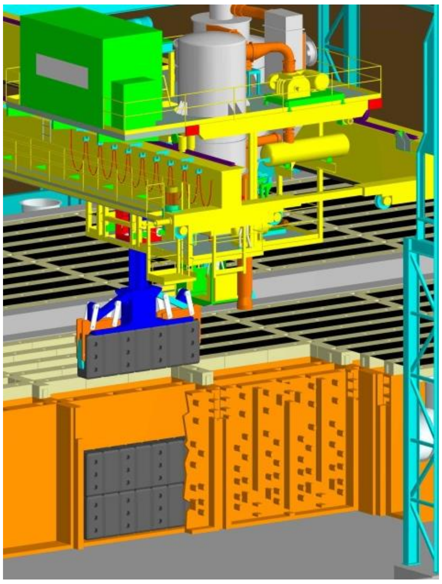


Figure 9: Anode handling and flue design

The upper part of the top row anodes is no more sufficiently baked. A solution is to load seven rows of anodes horizontally into the pits, reducing the section charge from 188 to 180 tons (Table 8). To ensure a sufficient packing coke layer above the anodes, the flue walls height is increased by 10 cm. Such a small change of the refractory height is acceptable in view of the required crane clearance.

Baking of 380’000 t/year of anodes in furnaces initially planned for 280’000 t/year (+ 38 %) leads to insufficient anode quality with too high variability due to following reasons:

- Total heat up time 149 hours does not allow a homogeneous anode heat treatment.
- Increased waste gas volume of 38 % doubles the pressure drop in the flues.
- Higher pressure drop in the flues leads to a lack of oxygen in the fire zone (soot formation).
- Correction of lack of oxygen by lower energy input is deleterious for the anode quality.

With the existing furnaces, the production of the total required BENCHMARK anode quantity is impossible.

An addition of one fire to a baking furnace can solve the capacity limitation. Table 8 shows the operation parameters with 7 fires. They are similar to the actual situation. The following investments must be considered:

- Extension of the furnace building
- Concrete tub
- Insulation and refractory (6’400 tons)
- Firing equipment
- Additional multipurpose crane (optional)
- Additional anode transport, handling and slotting equipment
- Waste gas cleaning facilities expansion
- Increase of the existing flue height
- Clamp adaptation on the existing cranes for horizontal anode setting
- Refurbishment of existing anode bundling and transport equipment (horizontal arrangement)

The investment cost for this expansion and adaption is estimated to be within 50 to 70 million USD.

Merchant benchmark anodes

Investment of 70 to 100 million USD in paste plant and baking capacity can be avoided by the purchase of 55’000 t/year of merchant anodes. The price of delivered merchant anodes should be compared to the production cost of in house anodes including additional capital cost.

By purchasing merchant anodes [13] the following should be considered:

- Availability: Long term contracts with optimum lot sizes (10’000 to 20’000 t/lot)
- Price: Raw material or LME related
- Quality: Specifications for benchmark anodes
  Determination and monitoring by third party laboratory before shipping
  Defined action if anode lots are out of specifications

The impacts of purchasing merchant anodes combined with reduced in house production are:

The green paste production decreases from 420’000 to 357’000 t/year. This allows the production of green anodes with the required quality values and consistency without further investment. Optimum process parameters (e.g. temperatures, pitch content, mixing and vibrating conditions, …) for the reduced throughput must be defined.

Paste plant	**Unit**	**In house production**
Green paste production	t/year	357’000
Green anode weight	kg	1'120
Green mill throughput	t/h	2 x 31
Specific mixing energy	kWh/t	9.1

Table 9: Paste plant production parameters with reduced throughput

The baking furnaces remain at six fire operation. Anode handling facilities have to be adapted to the horizontal anode loading in the pits. The height of flues and headwalls must be increased by 10 cm (400 tons of refractory material). The estimated cost is within 5 to 8 million USD.

The total heat up time of 174 hours together with the horizontal loading of the anodes allows the production of benchmark anodes.

Baking Furnace	Unit	In house production	Merchant anodes
Baked anodes requirement	t/year	325'000	55'000
Production per fire and year	t	54'200	
Tons per section	t	180	
Fire cycle time	h	29	
Total heat up time	h	174	

Table 10: Baking furnace production parameters with 6 fires

Summary

Increase of line current is a common way to improve the profitability of existing smelters.

Potlines with 300 kA built in the mid-nineties reached in less than two decades the impressive level of more than 360 kA. A further increase to 410 kA can be achieved by the latest magneto-hydrodynamic (MHD) and thermal-electrical (TE) optimization and design and material improvements.

The influence of the variability of anode properties on cell stability was investigated. With TE and MHD computation, the influence of baked apparent density, specific electrical resistance, thermal conductivity and butts cross section on anode current distribution and cell thermal equilibrium was quantified. This was applied to a significant potline current creep scenario.

Based on these results, targets for anode quality variations for cells with anode current density above 0.9 A/cm^2 have been defined.

Solutions for the production of benchmark anodes in the existing carbon plant and the necessary investments are described. Estimated investment cost of up to 70 million USD for paste plant and baking furnace modifications have to be expected. To avoid these investments, the purchase of merchant anodes is a real and safe alternative to bridge the additional anode demand.

Prior to any smelter modifications, however, a feasibility study should be executed to investigate the optimal solution for cell design and its impact on anode quality and anode requirement.

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