Rhodax Process – Recent Evolution and Future Challenges

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Abstract

The Rhodax® process is the result of two parallel developments started in early 1990s. By beginnings of 2000s, Fives and Aluminium Pechiney (AP now Rio Tinto) joined their R&D efforts and co-patented the SCAP-RHODAX® process.

This paper summarizes in a first part, what are the key initial characteristics of this process, how it performed over the past 25 years.

In the second part, it describes how the return on experience from the customers, forced the evolution of this technology to address new challenges faced with either variability in raw coke properties, maintenance issues, continuous amperage creeping resulting in high anode current density requiring even higher stable anode quality or again better energy efficiency to lower their carbon footprint.

Then the paper presents the studied technology developments (equipment, process and digitization), those which have been successfully implemented and also those requiring further R&D work.

Keywords: Aluminium electrolysis anode, Rhodax crusher, Fives.

1. Introduction

For the past 25 years, SCAP-RHODAX® process has been a best-seller technology with nearly 3 Mt of anodes produced annually by 12 green anode plants (GAP) over the world, half of them operating in the GCC countries and India.

Along these years and based on the return on experience from our customers, needs for evolution of this technology were identified. Indeed, new challenges are faced by users including:

- Higher variability in raw coke properties requiring higher process resilience
- Maintenance issues due to more intense use of the equipment or new maintenance practices with lower planned shutdown frequency
- Continuous amperage creeping requiring bigger anodes with even higher and more stable anode quality
- Request for higher energy efficiency to lower carbon footprint
- Or simply, technology driven with more electronic or digital functions

This paper summarizes the studied technology developments (equipment, process and control), those which have been successfully implemented and also those still at R&D stage.

2. RHODAX® Technology at a Glance

2.1 History and Reminder of Forgotten Technical Features

The Rhodax process is the result of two parallel developments started in early 1990s. In early 2000s, Fives and Aluminum Pechiney (AP now Rio Tinto) joined their R&D efforts and co-patented the SCAP-RHODAX® process (Figure 1) which consists mainly in:

- Mixing all solids (raw coke, green and baked scraps) and crush them all together at the same time without any detrimental impact on anode quality,
- Producing a recipe based on two size fractions only:
  - o Fines with 70 wt.% of particles smaller than 32 µm (< 32 µm),
  - o Grains from 300 µm to 30 mm.

Both leading to a drastic flow sheet simplification.

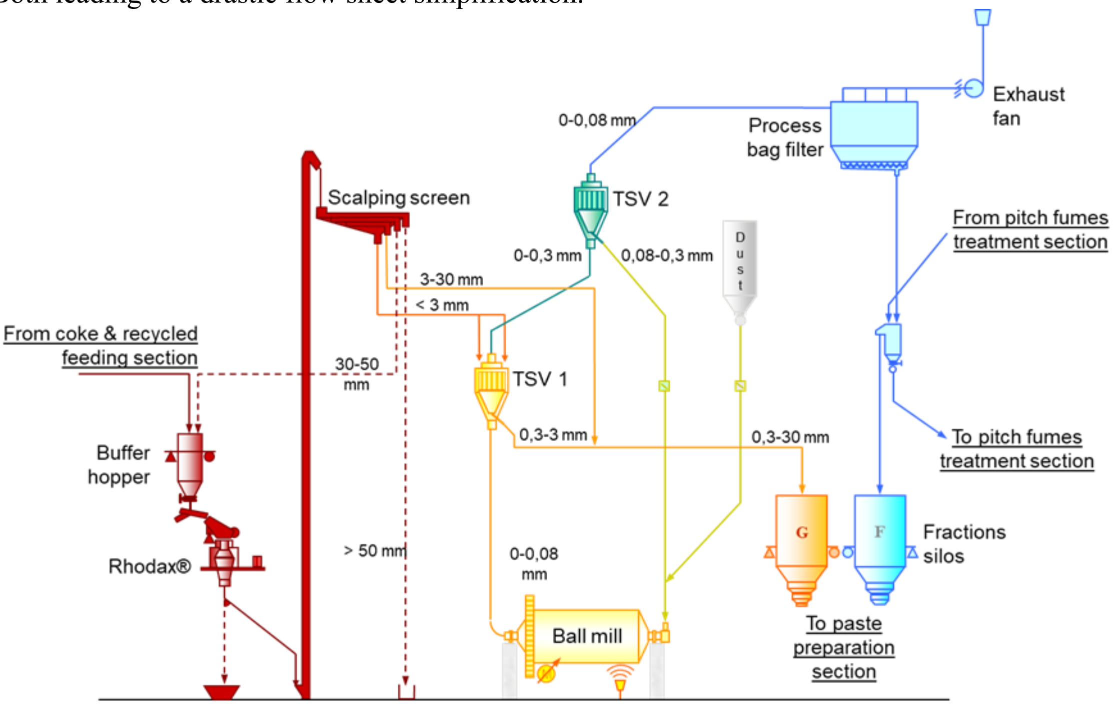

Figure 1. Original RHODAX® dry mix preparation line.

The key implementation characteristics and advantages of this technology are well known and described in [1]. In addition to the naturally high G/S (Grains/Sands fractions ratio > 4) and simplified flowsheet, several other important (and often forgotten) underlying technical features are recalled below.

First, the in-bed compressive grinding principle is a key technical differentiation factor of the Rhodax crusher compared to any other type of conventional crushers like cone crusher for instance. When it comes to crush together the fresh coke and the harder butts, it allows preservation of the crushed butts on the coarser side (selective crushing) preventing production of fines from them while crushing, in priority, the porous fresh coke particles. Moreover, as shown in Figure 2, initial tests also demonstrated a better cubicity of the particles, measured with the flakiness index, which is known to lead to better bulk density [2] of the dry mix and which was also verified with the Rhodax crusher.

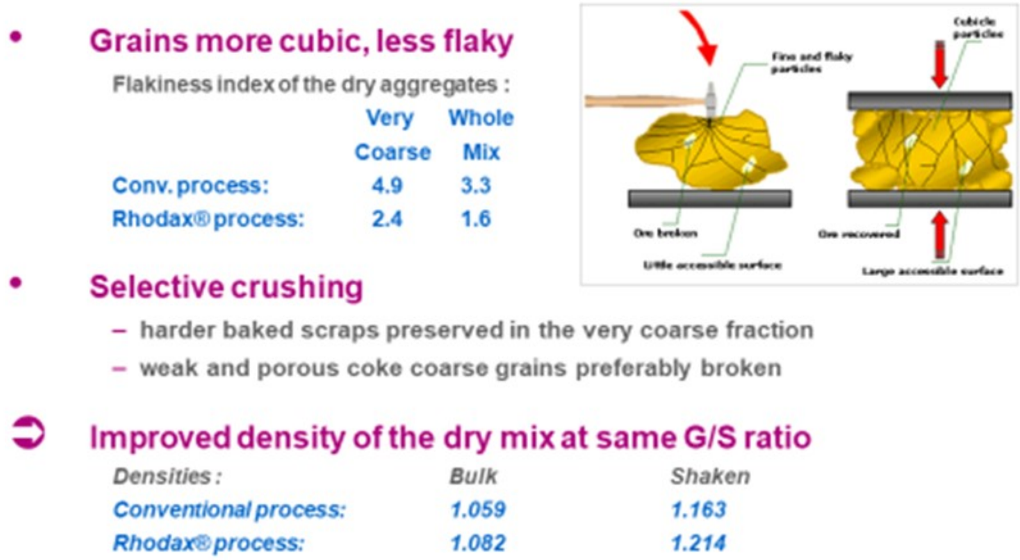

Figure 2. Impact of the selective crushing on particle shape and dry mix bulk density.

The other advantages of this type of crushing as illustrated in Figure 3.

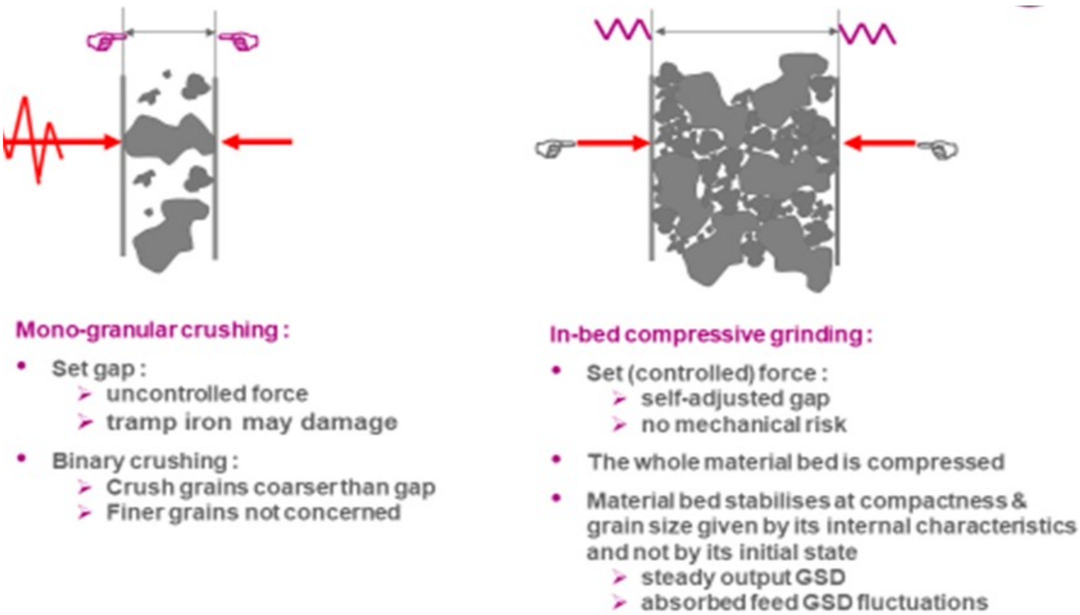

Figure 3. Mono-granular crushing as happening in conventional cone crusher (left) vs In-bed compressive grinding as happening in Rhodax crusher.

Another key feature is a circuit designed to control the quality of the fraction < 32 µm rather than the quality of the fraction < 74 µm, as for the conventional processes. Controlling accurately the fraction < 32 µm is possible thanks to the very accurate cut size of the TSV dynamic classifier combined with the control the ball mill circulating load. Together, they make a huge difference when it comes to fine quality stability.

Figure 4 shows various ball mill coke fine grinding pilot tests results comparing the blaine number as a function of particle size distribution, expressed as cumulative retained percentage at 74 µm and 32 µm. In conventional process the fineness of coke fines is close to a blaine number of

4 000 cm²/g, corresponding to 80 % of the coke particles with a size smaller than 74 µm (20 % cumulative retained) and 45 % smaller than 32 µm (55 % cumulative retained). In Rhodax process, the fineness of coke fines is close to a Blaine number of 6 000 cm²/g, corresponding to 98 % of the coke powder with a size smaller 74 µm or 70 % smaller than 32 µm.

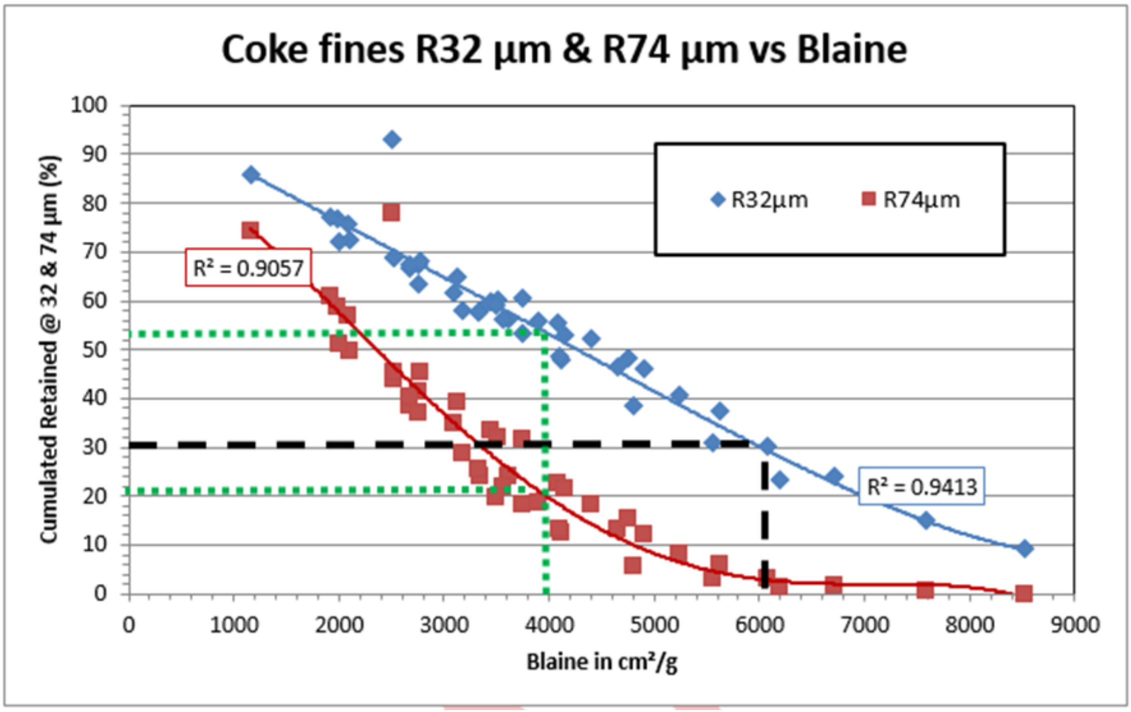

Figure 4. Cumulated retained at 32 µm (blue diamond dots) & 74 µm (red square dots) vs Blaine number.

High G/S ratio requires significantly increase in the fineness of the coke fines. This is easy with the Rhodax process specifically designed to produce high fraction of particles < 32 µm in the coke fines. As shown in Figure 4 (blue line), the sensitivity of the fractions < 32 µm versus Blaine number remains constant even at a high fineness, meaning that a good control of the fraction smaller than 32 µm will lead to a good control of the Blaine number.

Several conventional green anode plants decided to increase the G/S ratio by increasing the fineness of their coke fines with a higher fraction of < 74 µm target. As shown in Figure 4 (red line), when pushing the fineness above 4 000 cm²/g and following the fraction < 74 µm, there is a significant loss of sensitivity with the Blaine number meaning that it is likely to lose its control. A well-documented example of such situation is described by R&D Carbon [3]. A solution in that case, is to upgrade the fine grinding circuit with a similar solution implemented for the Rhodax process which consist in installing a dynamic classifier with accurate control of the cut size and a control loop to stabilize the ball mill circulating load. To illustrate the fineness stability that can be achieved with such set-up, Figure 5 hereafter shows the fine stability of a such circuit monitored over a period of 15 days. The Cpk ratio shows the relationship of the process spread to the specification limits while taking into account the centering of the process compared to the specification limits. In general, the higher the Cpk, the better. A Cpk value less than 1.0 is considered poor and the process is not capable. A value between 1.0 and 1.33 is considered barely capable, and a value greater than 1.33 is considered capable. In practice, a good process under control should target a Cpk value of 2.00 or higher where possible.

2.2 Performance and Challenges

The initial version of the Rhodax process has strongly evolved over the years, both in terms of process parameters, process control and equipment design.

On the process side, the main evolutions deal with the granulometry at various points in the circuit.

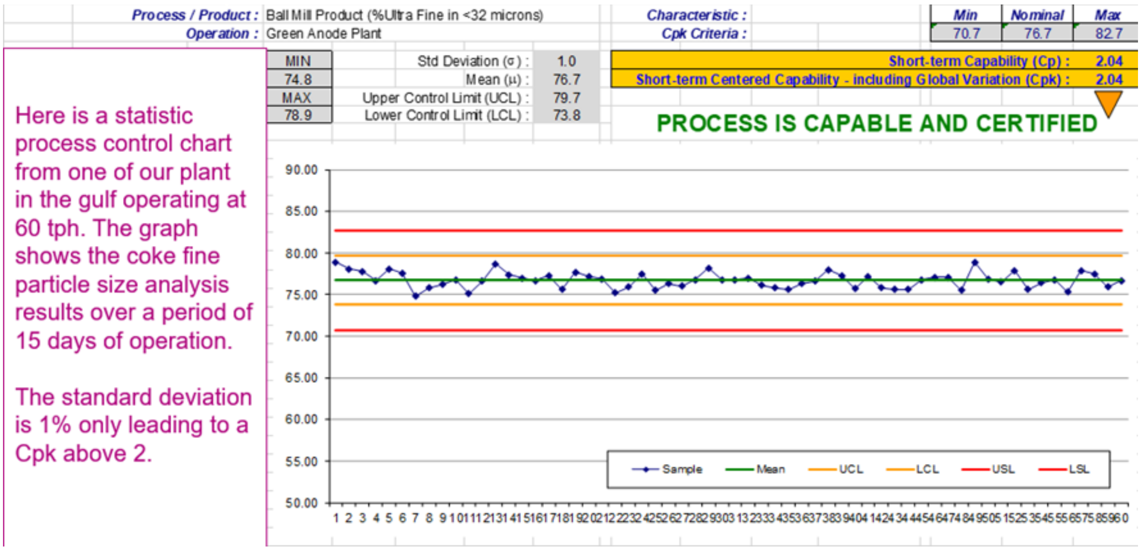

Figure 5. Fine quality stability measured with fraction of the particles <32 µm and Cpk.

On the feed of the circuit, both the fresh coke and recycled scraps size distributions are fluctuating more often and with a a much wider range. For the fresh coke, the 80 % passing size can vary by a factor of 2 (10 to 20 mm) which is either due to higher segregation in the huge coke storage silo at the port [4] or due to the variable mixture of both rotary calcined coke and shaft calcined coke [5, 6]. For the recycled scraps, the 80 % passing size can vary by a factor of 3 (20 to 60 mm) which is due to either the variety in the design of the crushing recycling units with different types of crusher technologies or different number of crushing stages.

On the output of the circuit, the top size of the dry mix material which was initially set to 30 mm, has been reduced in some cases down to 20 mm and even 16 mm. Good technical reasons motivated this reduction in size:
- The reduction of the preheating screw wear rate
- The elimination of the risk of particle segregation in the green anodes
- Or suspicion of the negative impact on the electrical resistivity of the baked anode [7]

On the intermediate circuit stage, the cut size of the material feeding the first dynamic classifier have been reduced from 3 mm down to 1.7 mm to strongly reduce its wearing rate.

Concerning the process control, various options were successfully implemented in order to improve the circuit stability. The earliest one was the concept of virtual fine silo, followed by the development of a coke fine size distribution controller (Optibinder) [5]. Lately, a new circuit design without the first dynamic classifier (Rhodax S circuit) was successfully tested [8] in order to guarantee a G/S ratio closed to 4 while improving the controllability of the circuit by adding a massflow controller on the feed of the fine grinding circuit.

On the equipment side, the main evolutions include:
- The Rhodax 4D model to increase the crushing capacity and flexibility of the circuit
- The new Rhodax liner design to increase lifetime

- The variable speed drive (VSD) on the ball mill instead of a hydraulic coupling for a better speed and milling power control
- The new dynamic classifier design to ease the maintenance and increase the lifetime of wear components
- The addition of an eddy current separator upstream in order to remove the aluminium chips which were causing too many short stoppages of the crushers.
- And eventually, the new fine dosing system [5] in order to stabilise the very fine coke fines of the Rhodax process.

All these challenges listed here above lead to technology evolutions. Some of them are detailed in the rest of the paper.

3. RHODAX® Technology Evolutions

3.1 Evolution Industrially Tested

3.1.1 Rhodax S Process

The New Rhodax S Process takes into consideration the large experience from the previous installations and aims at further improving the process stability, while maintaining the G/S at 4 for a full benefit on the thermal shock resistance of the anodes. As shown in Figure 6, the scalping screen has one more cut size of 1 mm. This new size fraction goes to an overflow feeder coupled with a flow controller. This new arrangement replaces the first dynamic classifier in the Initial version and allows an easier control of the coke quantity sent to the fine grinding unit by adding a massflow controller on the feed of the fine grinding circuit.

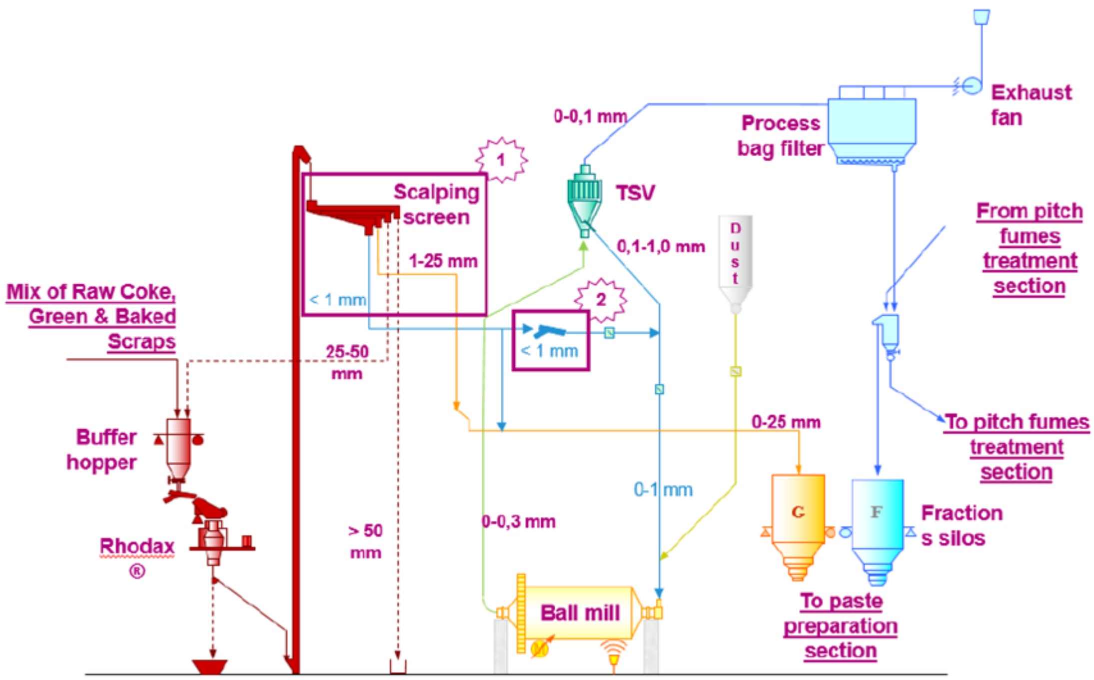

Figure 6. Rhodax S simplified flowsheet.

The Rhodax S design has been already successfully industrialised in 2018 at Xinfa (China) with two 60 t/h Green Anode Plants. Anodes Quality and Performances in pots are comparable to highest standards as described in [8].

3.1.2 Rhodax 4D Crusher

The New Rhodax S process was also the opportunity to implement the new Rhodax crusher model 4D to increase the crushing capacity and flexibility of the circuit (Figure 7). All counterweights positions are controlled at any time by the VSD. The electronic synchronization replaces the mechanical one which was done via rotary actuator and belt. As a consequence, the machine is easier to control and to maintain. Crushing force can be controlled directly from the SCADA (Supervisory Control And Data Acquisition) system by adjusting the angle from idle mode (No crushing) to full crushing. This is giving a lot of flexibility to the operator to overcome entry material deviation (shaft or rotary coke) or recipe change due to lack of baked recycles for example (lower crushing force required).

On maintenance side, reference point for synchronization is easier: counterweights are manually positioned in idle mode and angular reference is just recorded by a simple click from the SCADA. Combined with the new material of liners, it allows a better reliability and higher tonnage of material to be crushed with the same wear parts.

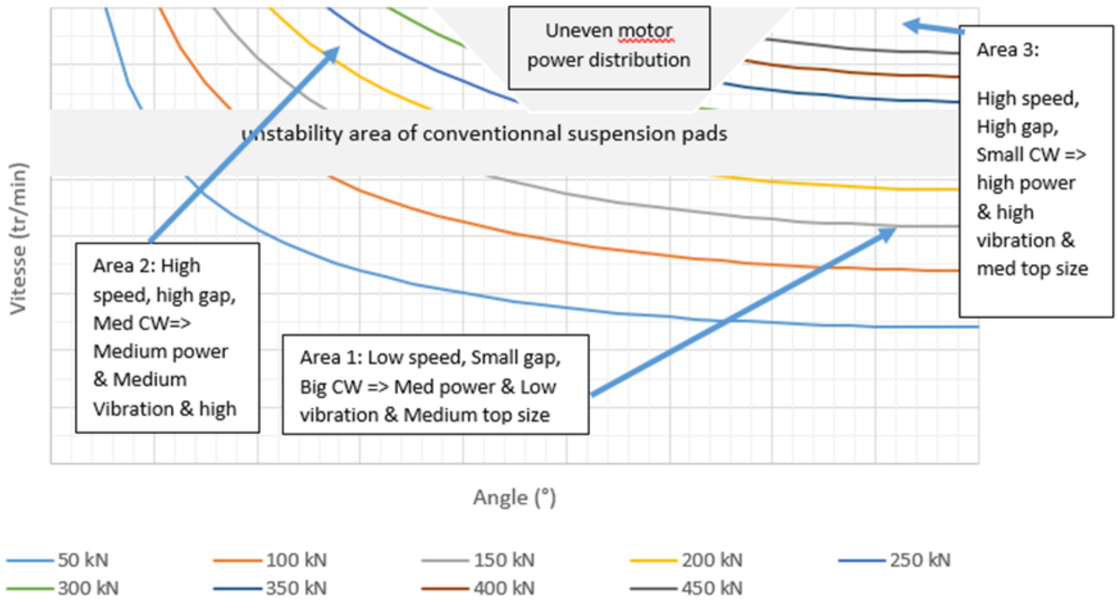

Figure 7. Rhodax 4D – Working area function of speed, counterweight (CW) angle.

3.1.3 Dry Mix Top Size

The dry mix material top size of the existing circuits has been reduced from 30 mm initially down to 16 mm leading to a higher particle size reduction ratio and higher crushing effort. As consequence of this top size reduction, wear rate of the downstream equipment is reduced and appearance of anodes is better.

To reduce the top size, meshes of the scalping screen are modified and size fraction recirculated to the Rhodax crusher changed from 30/50 mm to 16/50 mm. This has big impacts on the flow balance of the circuit and requires some adjustments:

- Efficiency of the screen decreases a lot leading to an increase of the recirculation load of the circuit. One solution is to achieve the 16 mm cut size in two steps with two screen decks.
- As the circulation load back to the Rhodax crusher, increases, the crusher gap (closed side setting) opens to accommodate a higher output leading eventually to uncrushed coarse coke

particles in the recipe and an excessive amount of +13.2 mm size fraction in the final dry mix recipe.
To prevent these negative side effects, it is possible to improve the crushing efficiency of the upstream recycled crushing unit. For instance, upgrading the crushers with hydraulic double roll crusher coupled with new sleeve with corrugated design to achieve a smaller baked and green recycle top size. It is also possible to increase the Rhodax crushing circuit capacity as detailed in section 3.3.

3.1.4 Dynamic Classifier: TSV "Coke" & Cut Size

Rhodax process is based on the accurate cutting size of the TSV dynamic classifier. Extension of their lifetime while keeping its size partition curve efficiency is achieved through two type of actions:
- Major upgrades in design with new lining material, new manufacturing process and simpler control solution lead to a more robust machine compatible with the existing layout. It means that this new machine can replace existing one without impact on the installation. It has been implemented already at more than 10 locations and operating for more than 6 years for the oldest one. Achieve performance is as expected:
  - o On process side, the cut-size efficiency remains unchanged
  - o Lifetime has increased by a factor 4, as after 5 years of operation, TSV is still in very good conditions (Figure 8) with much a lower maintenance requirement.
- The cut-off mesh of the TSV1 feed has been reduced from 3 mm to 1.7 mm. Indeed after analysis of the granulometric data at screen inlet, the quantity of material under 1.7 mm was sufficient to produce the quantity of fines required by the process. The feeding of TSV1 with granulometry below 1.7 mm not only allowed a better separation efficiency (lower load) but also a significant increase in the TSV1 life time (finer material means less abrasion).

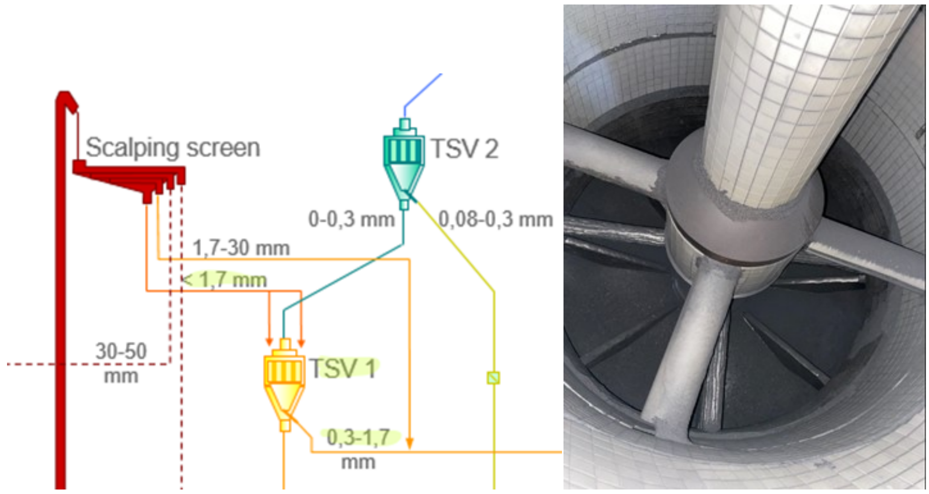

Figure 8. Dynamic classifier TSV1. Left: Position in the flowsheet, Right: Internal lining.

3.1.5 Coke Fine Dosing Unit

Stabilization of fines and ultrafines content in the dry mix is essential for good paste quality, stabilize pitch demand and therefore stabilize the green anode quality. To achieve that, both fines stable particle size stability and very accurate proportioning are required. The dosing systems used for fines must be dust-proof and allow continuous dosing with an accuracy below 0.5 %.

Up to a certain level of fineness, loss-in-weight hoppers meet these criteria quite well despite the interruption in weight measurement while filling the hopper, a certain sensitivity to pressure variations and the risk of flushing. After the transition to Rhodax process, with much finer coke fines, these flushing phenomena became more accentuated and the loss-in-weight fines dosing systems were replaced by Rotor Weighted dosing systems as shown in Figure 9. This is now the standard set-up.

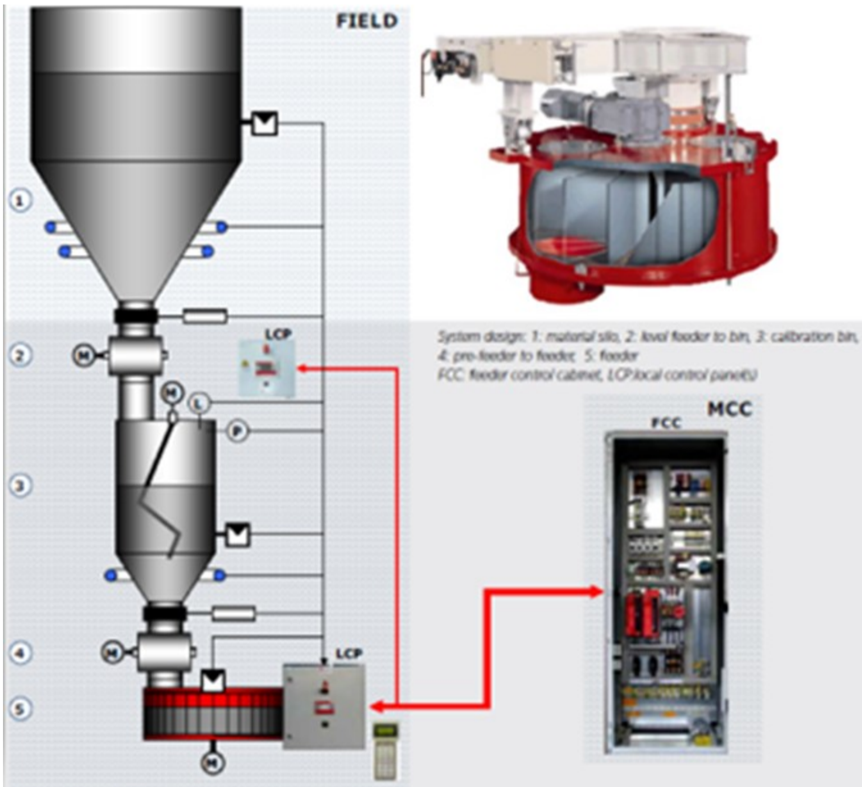

Figure 9. Fine dosing unit set-up (by courtesy of Pfister).

3.2 Evolution Tested at Pilot Scale

Aluminium industry is more and more challenged with CO_2 emissions and aims at reducing these emissions at all stages of the process. The Horomill fine grinding machine is one good candidate. It is an energy efficient grinding technology based on the same in-bed compressive grinding principle as in roller presses, vertical mills or Rhodax crusher. This high-pressure grinding mill is developed by Fives and well-known in cement industry. Several pilot tests were conducted from 1995 to 2014 to produce coke fines for green anode plant [1]. The grinding efficiency of the Horomill is 40 % lower than the ball mill and similar to the vertical mill which is in the same grinding class (pressure vs compactness). However, when considering the energy consumption of the whole grinding circuit (including fan power and other pieces of equipment like dynamic classifiers or crushers), the Rhodax + Horomill circuit appears to be one of the most efficient (Figure 10).

kWh/t	Rhodax + Ball Mill	Cone Crusher + Vert. Mill	Rhodax + Horomill
Grinding mill	63	39	39
Filter Fan	8	25	12
Others equipments	8	13	8
Total	**78**	**77**	**59**

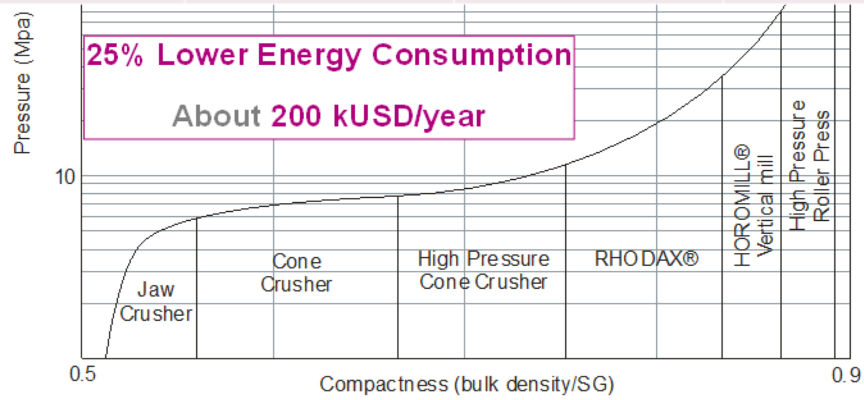

Figure 10. Specific energy consumption for 3 typical grinding circuits.

On top of that, the Horomill brings some other interesting technical advantages like:

- very small footprint in the plant (Figure 11),
- almost no iron pollution,
- low noise level (below 85 dBA at 1 m)

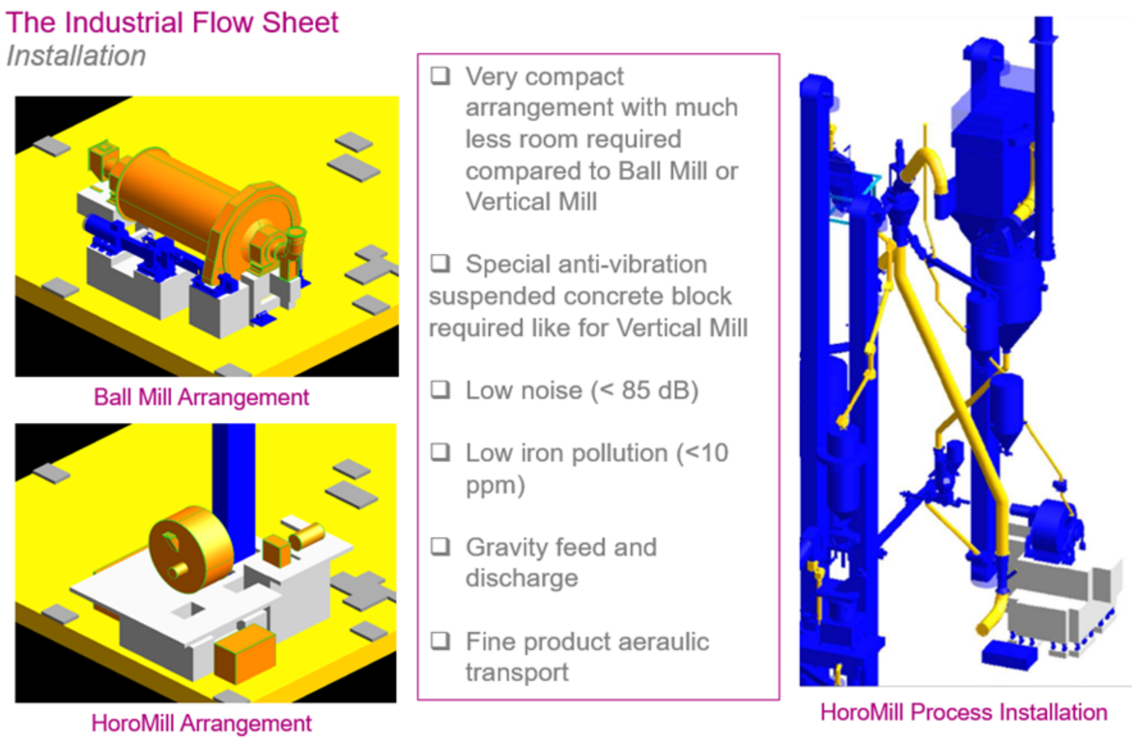

Figure 11. HoroMill versus Ball mill based fine grinding circuits.

Such new configuration of the circuit has not been industrially tested yet.

3.3 Evolutions to be Implemented Soon

3.3.1 Rhodax Crushing Circuit Capacity Boost

Few green anode plants [7] have reduced the top size of the dry mix material down to even 16 mm. Benefits like the equipment wear rate reduction or the lower segregation in the green anodes are noted but at the price of increased crusher circulation load and loss of green anode plant crushing capacity and flexibility. These plants have their own specificities that influence their performance:

- Top size of the baked recycled from 25 to 80 mm.
- Throughput of the plant require different machine sizes: Rhodax 600 for 35/40 t/h or Rhodax 1100 up to 60 t/h.
- Fresh coke particle size and type or production technology.

Therefore, after several circuit simulation studies and measurements campaigns on site, Fives has developed a new specific double roll crusher (DRC) to be located on the circulation load of the Rhodax on existing circuit in order to recover both more capacity and flexibility. The design of this roll crusher allows to fit all the cases. This DRC is sized to crush up to 17 t/h of product (mainly baked recycled) with a top size up to 30 mm. It has special features to ease its implementation in existing plants (Figure 12 – Right) with no impact on the structure, low vibration transmitted to close equipment, low maintenance requirements and easy control and monitoring. Thanks to the DRC, the section settings will be automatically adapted to limit top size at 16 mm and reduce significantly the fraction of grains larger than13.2 mm in the final dry mix recipe and therefore meet the pot technology package specifications.

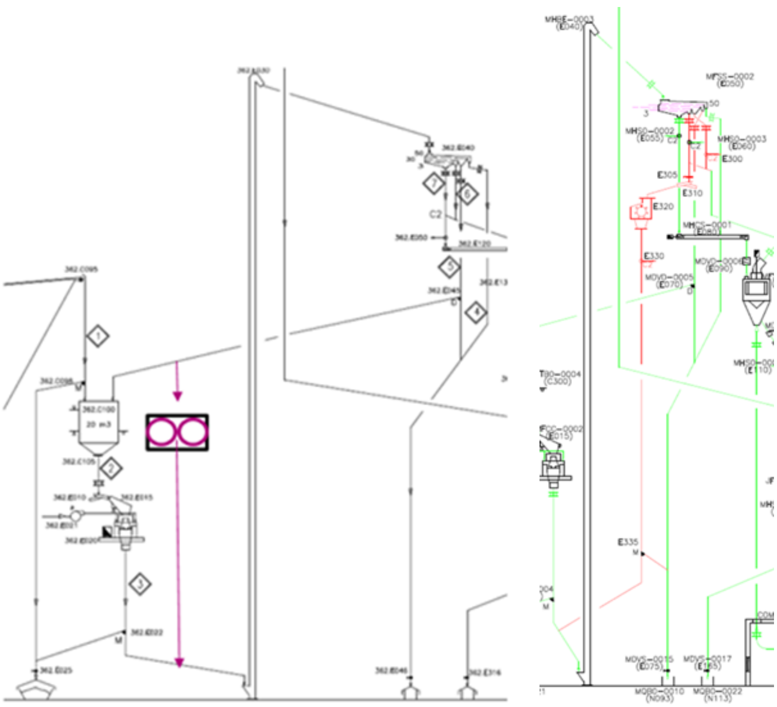

Figure 12. Left: New DRC fitted into an existing Rhodax process flowsheet, Right: Taylored Rhodax circuit modification.

3.3.2 Rhodax Crushing Circuit Flexibility Boost

Under particular circumstances, a tailor-made solution can be proposed to solve a unique problem. Due to special constraints, management of coke silo can lead to big variation of raw coke particle size distribution [4]. Entry material at the green anode plant can be temporarily completely out of initial technical specifications. Lack of one fraction will impact final product quality and cannot be totally compensated by adjusting the existing process parameters

Such a case happens [4] and investigation was necessary to find the root cause as well as to quantify the consequences on anode density variations. The root cause was a strong fluctuation of the size distribution of raw coke leading to a missing fraction in the worst situation.

A solution was proposed to produce the missing fraction by crushing one of the coarser fraction in excess, the 3–10 mm coke fraction, to less than 1.7 mm (Figure 12 – Left). Adaptation of the process requires modification of the screen and the addition of a new small dedicated crusher in order to recover flexibility to bring back the dry mix recipe into specifications.

3.4 Rhodax Process and More Advanced Features

The latest references of the Rhodax based green anode plants included significant digital features aiming at improving the process monitoring and performance [5, 9]. Few of them are dedicated to the dry mix preparation line:

- The coke fines on-line analyser (Figure 13) is a well-known technology and was already applied in that field of industry. Installed right after the dosing unit it allows a better control of the coke fines' quality with two types of actions: one manipulating the dosing unit, the other one the dynamic classifier speed to change its cut-size.

Figure 13. Fine particle size analyzer (by courtesy of Malvern).

- New modules of AMELIOS GAP Software [9] including:
  - o Automatic evaluation of the ball load inside the ball mill based on simple snapshot of the ball charge taken by a field operator during his routine weekly shutdown (Figure 14).

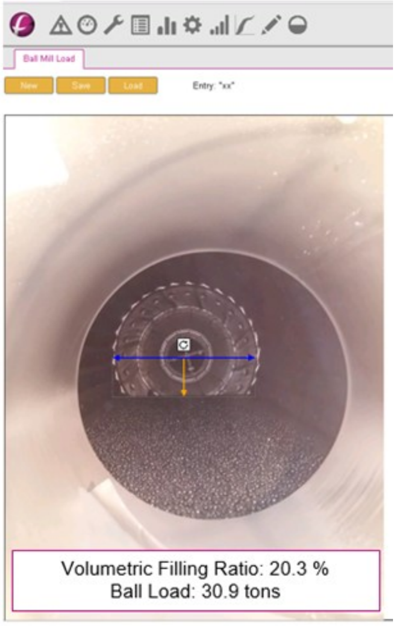

Figure 14 – Ball load calculator

o or a digital twin (Figure 15) of the dry mix preparation line combining phenomenological process model of each step (crushing, screening, fine grinding, classifying and material handling) with a population balance model in order to estimate in real time the mass flow of each stream as well as the particle size distribution. This type of real-time modelling opens the door to a future model-based control system in order to further improve the circuit stability or to detect process deviations early enough to limit their impacts on the anode quality.

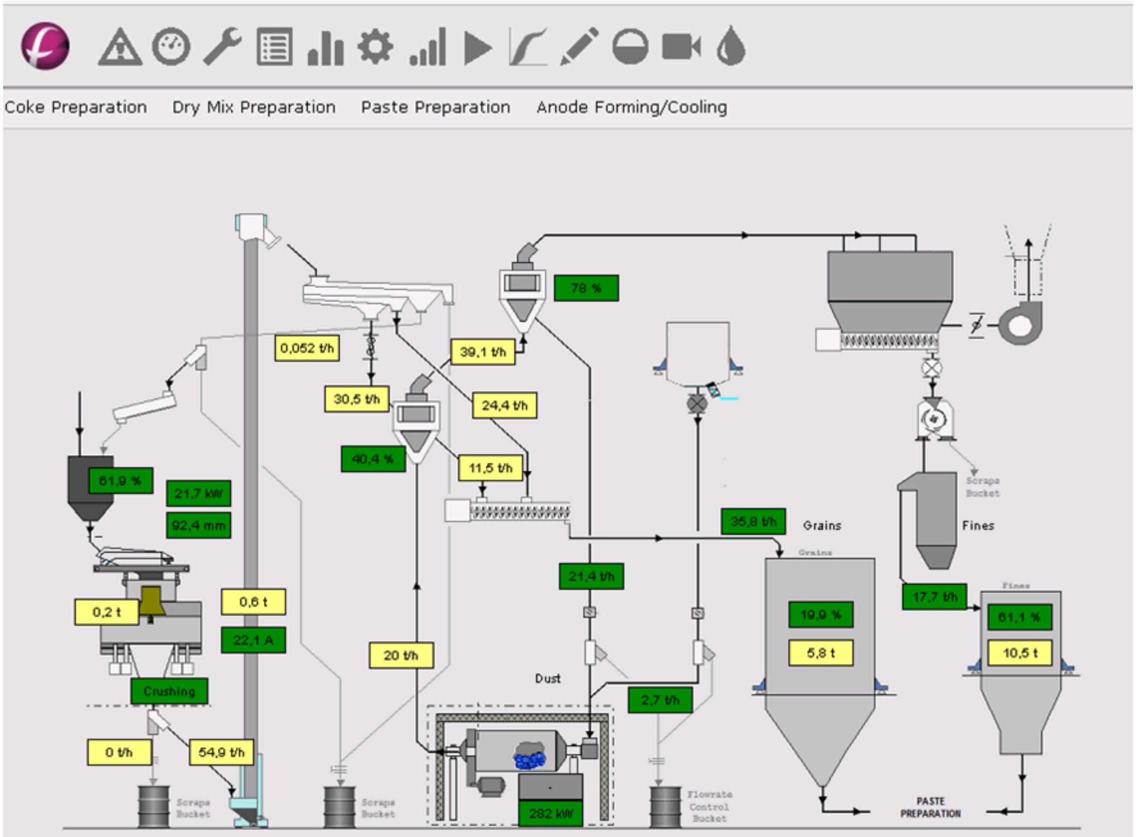

Figure 15. Auto-Adaptative on-line Population Mass Balance Model of the Dry Mix Preparation Line – Estimated mass flow for several streams.

4. Conclusions

Designed to implement the high G/S ratio concept developed 1990's, the Rhodax process came with a lot of other important features which were reviewed in this paper. Over the years, new challenges came and forced the continuous evolution of this technology to add new features dealing with process, control and equipment performance.

These new features aim at adapting the technology to user's new constraints (like raw material variability, new anode quality requirements or operation and maintenance) without jeopardizing the key initial benefits of the Rhodax process. A lot of these new features are already successfully tested at industrial scale and some others remains at R&D level, like high fidelity simulation of the crushing process to prepare the future of the green anode production.

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