

CB03 - Upgrade to Narrower and Deeper Slots in Anodes: Improving Efficiency and Mechanical Behavior

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Abstract

Business case for slotted anodes need not to be made anymore. Slots help reduce thermal stresses in the anodes lowering risk of cracking. They are an effective way to allow continuously formed gas escaping from underneath the anodes and thus reducing electrical cell resistance while improving pot stability. Slots also result in bringing down electrical power consumption during aluminium production. Depth of slots ensure that benefits last throughout the entire life of the anodes and finally slots with reduced width reduce the amount of carbon removed from anodes and extend anodes cycle time.

Anode quality is a key variable in an aluminium smelter overall efficiency and production costs. Smelters already using cut or molded slots in anodes can improve the benefits by increasing depth and reducing width of slots using Anode Slot Cutting Machine (ASCM) climb milling technology instead of conventional slot cutting. A climb milling technology upgrade allows for deeper and narrower slots (up to 450 mm deep and 9.5 mm wide). It can be more demanding on the control of anode movement across the cutting blades. For this reason, a climb milling upgrade includes changes to the hydraulic and electrical control systems but does not require increase in power. In addition, more fine dust is generated which in most cases requires an upgrade to the existing dust management system.

The new generation of ASCM systems with climb milling technology offers the ability to cut deeper and narrower slots in various geometries including optional interrupted slots. The spinoff of this is the ability to also upgrade existing systems. In addition, any upgrade of an ASCM can include the addition of a high degree of self-diagnostics, predictive maintenance and remote monitoring to detect alarm/abnormal conditions. This will allow operators to keep a close eye on equipment performance and predict blade and other failures before they occur. All this to reduce OPEX expense, increase uptime and to reduce blade consumption and associated costs.

Keywords: Climb milling technology upgrade, Energy efficiency of the electrolysis process, Anode handling Industry 4.0, Conventional anode slot cutting, Anode resistivity measurement.

1. Introduction

High cost of energy and volatile metals prices are driving primary producers of aluminium to optimize their processes to stay competitive and profitable in a very tight market.

Since 2003, Anode size have increased considerably. Anode slotting got introduced within the Primary producers' process when they started using larger anodes. With a larger carbon block, larger surface, greater resistance to release gases from the electrolysis translating into energy losses and lower performances. At the beginning anodes were about 130 cm (L) × 65 cm (W) × 55 cm (H). Nowadays, it is common to work with anode size of roughly 165 cm (L) × 100 cm (W) × 60 cm (H). Although, in 2018 a significant increase of anode production costs brought primary aluminium producers to the analysis of what can be done to minimize the impact [1]. For

the ones already practicing anode slot cutting, the challenge was thrown at equipment designers to reduce the width of the slots and make them deeper for a better life cycle.

2. Brief History of Slotted Anodes

Figure 1 shows the evolution of anode slots from the traditional unslotted – caricatured as primitive, to mold-formed, and saw-cut – caricatured as intelligent.

- In the 1980s, ever increasing amperage and corresponding increasing anode size was causing anode cracking due to thermal shock as well as anode effect (perfluorocarbon gasses trapped underneath the anode) which reduced cell efficiency.
- Through the 1990s trials were done at aluminium smelters to overcome this problem. Examples of these trials were: In 1994, Aluminium Alouette underwent a trial to replace the twin AP30 anode with a single double wide block [2]. The cell current efficiency dropped by 3.6 % and the deterioration was attributed to CO₂ gas bubbles twice the normal size. In 1993, Hydro Aluminium also performed tests which entailed splitting of the anodes in two. This had the opposite effect on cell noise and current efficiency.
- Slots were first introduced to solve anode cracking issues and it was only later discovered that the slots had additional benefits.
- In 1998 both Rio Tinto [2] and Alcoa [3] started using slotted anodes on a production scale.
- In the early 2000s, slot sawing was at the beginning of industrial use and since then, slot sawing has been continually refined and accepted by many technical authorities as best practice for manufacturing anodes for aluminium production.

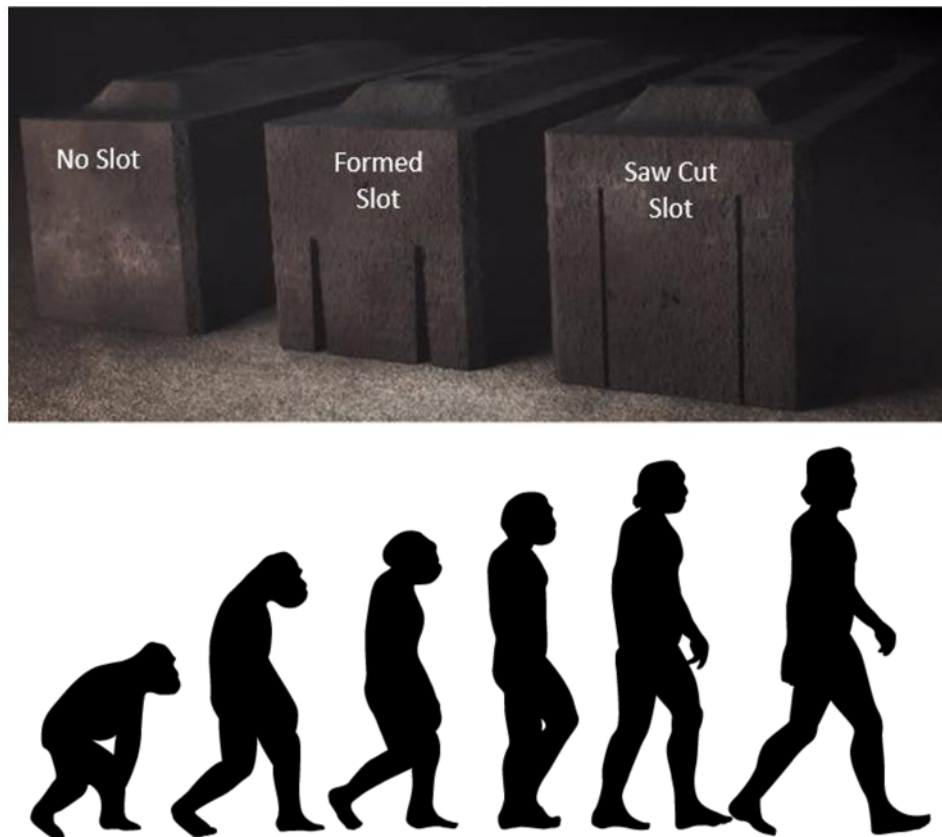


Figure 1. Evolution of the prebake anode slots [4].

3. Advantages of Saw-cut Anode Slots versus Formed Slots [5]

Main advantages of cutting slots versus forming slots are as follows:

- Formed slots must endure multiple handling steps as well as the baking process and thus cannot be made deep enough to be effective through the life of the anode in the pot. Anodes with slots sawn do not have to endure this (as slotting is done after baking) and thus can be made deeper and be effective longer.
- Flexibility and orientation of slot geometry can be as required for the pot and not dictated by the anode forming compactor geometry.
- Cutting slot parameter and geometry can be easily and instantly changed with machine program, whereas any changes to formed slots asks for time consuming shutdown, replacement of blade on vibro-compactor / press.
- When forming slots in anodes, areas around the slots vary in density and thus are less homogeneous, even cracks are noticed at the end of formed slots. Anode blocks with sawn slots have a more consistent density profile throughout the block and as a result perform better in the pots.
- Packing material can be hard to clean out of formed slots while sawn slots arrive at the potline completely clean. This removes one source of pot dusting which reduces pot efficiency.
- Sawn slots can be narrower and thus leave more carbon for the reduction process.

There are a few disadvantages as well to sawing versus forming slots which include:

- the capital cost (CAPEX) of the slot cutting equipment,
- the operating costs (OPEX) of the cutting tools,
- required temperature management of the anodes being transported from the anode bake furnace to the slot cutting machine, and
- recovering the cut carbon chips and transporting them back to the green anode plant.

To briefly elaborate on the above disadvantages:

- the CAPEX on the installation of slot cutting into a smelter can cost from 3 M\$ to 10 M\$ for smelters producing 250 kt/y to 700 kt/y.
- The OPEX on cutting tools will conservatively be in the range of 1 to 2 \$ per tonne of aluminium production.
- Slots to be cut in anodes must be done after the baking process. The typical design temperature of baking is 1150 °C. and the design temperature of anodes leaving the bake furnace is 350 °C. The maximum temperature that can be cut using known technology blades is 250 °C and preferably lower to maximize the diamond cutters blade life. This temperature management, in some cases, will require additional material handling steps.
- Carbon collection of about 20 kg per tonne of carbon or about 8 to 10 kg per tonne of aluminium production is required. This is an extra process step.

Aluminium producers considering the introduction of slot cutting into their operating plants have to prepare a business case, and for most, the efficiency benefits, environmental advantages and cost savings outweigh the CAPEX and OPEX costs. Deeper slots result in either a) lower voltage drops across the pots (reduced energy costs) or b) the ability to increase amperage and thus an increase in production of aluminium [5].

4. Conventional Cutting versus Climb Cutting of Slots

Conventional cutting and climb cutting are two different approaches to cutting materials, commonly used in sawing. The main difference between the two lies in the direction of tool movement relative to the work piece and how each method affects the cutting process.

In conventional cutting, the cutting tool rotates in the opposite direction to the feed motion (see Figure 2) of the work piece. This means that the tool's cutting edge is against the direction of the feed, resulting in the tool "biting" into the material and gradually removing material as it advances. In this process, the cutting forces tend to push the work piece against the table, which helps maintain stability during the cutting operation.

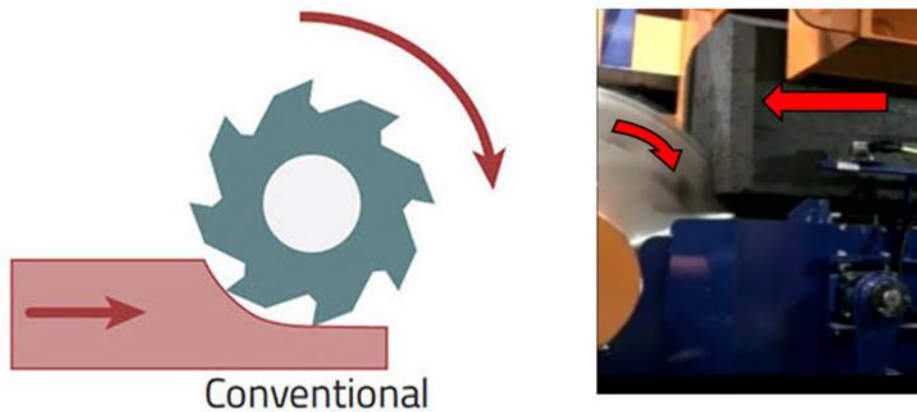


Figure 2. Illustration of conventional cutting method.

In climb cutting, the cutting tool rotates in the same direction as the feed motion of the work piece (see Figure 3). This results in the cutting edge engaging the material and removing material before being pushed away from the direction of feed. The tool tends to pull itself into the material. The working forces of feed versus tool bite work in the same direction. In the case of anode slot cutting, this can result in unstable vibrations due to backlash in the feeding trolley drive and guidance mechanisms.

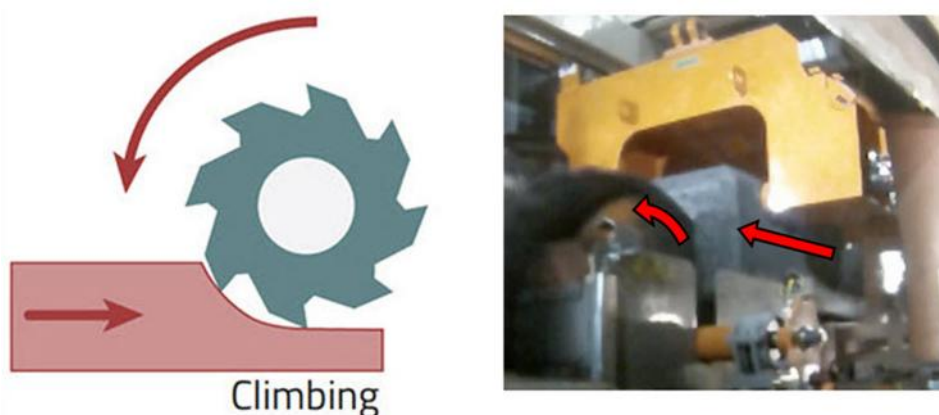


Figure 3. Illustration of climb cutting method.

Early slot cutting machines were mostly set-up in a conventional cutting configuration which is more forgiving on machine set-up and easier on tool life which was and still is very important. Conventional cutting is the preferred set-up by machinists for rough cutting where the cut does not need any special surface finish or tight tolerance.

However, to achieve minimal slot width and maximum slot depth, it is the climb cutting method that needs to be used. To go deeper on a slot, we need larger diameter cutting blades. With larger diameter blades, the body thickness of the blade must be increased to allow the cutting disk to withstand the cutting forces without distortion. In order to keep the blade as narrow as possible, the addition of blade guides is necessary to assure that the blade cannot deflect off course before entering the material to be cut. In the case of conventional anode slot cutting, blade guides cannot be added to the saw blade entrance of the anode as the anode moves through this zone during the cut. Therefore, the only way to add blade guides is to use the climb cutting method.

5. Challenges Associated with Converting from Conventional Cutting to Climb Cutting

For new slot cutting machines which were designed for climb milling, the challenges are well known and are well managed by the specialized machine suppliers. As for the existing machines on the market dating back to the early 2000s, there may exist the opportunity for converting them to climb milling and gaining the benefits of deeper slots without the cost of an entire new system.

The machines that exist in the industry are not all the same, but they all share the same fundamental challenges associated with a potential conversion to climb milling.

The first challenge is an assessment of the machine backlash on the mechanism which moves the anode through the blade(s) or the saw blade(s) through the anode. Backlash refers to a mechanical clearance or looseness between mating components or moving parts. It is the amount of free movement or play that exists between two connected parts in a system. In the case of the slot cutter, it is between the fixed part of the slot cutting frame and the moving mechanism.

This mechanism has two key components which must be evaluated:

1. The driving mechanism (hydraulic cylinder, electric cylinder, rack, and pinion). Every part in the drive chain must be looked at carefully because any backlash in the driving mechanism may not show up as a problem for conventional cutting but it will be critical for climb cutting.
2. Guiding mechanism – for both conventional and climb milling it is important to have very rigid and precise guidance of the anode or blade (whichever is moving). Looseness or backlash in this area of the machine must be minimized. In a conversion from conventional to climb cutting, this must be evaluated and changed for new parts if excessive wear is present.

The second challenge is the evaluation of the driving mechanism's control system. With either cutting method speed feed control has to be precise and repeatable but with climb cutting, the controller will have to deal with push and pull forces during the cut cycle which is much more demanding when trying to accurately control the speed at the same time. In most cases, the conversion will require a replacement of the speed/ position controller.

The final challenge, and likely most invasive modification requirement is the control and collection of the dust generated by the climb cutting. It can be seen in Figure 2 that dust from the cutting operation is discarded directly below the blade into receiving hopper underneath the machine. As it can be seen in Figure 3, the dust leaves the top of the saw blade and is propelled forward through the air and collected by a hopper with a large downdraft. In systems evaluated by the authors, the chip and dust collection hopper need to be changed and the airflow of the dust extraction has to be doubled.

6. Advantages of Converting to Climb Cutting and Adoption of other Available Slot Cutting Machine Upgrades

The economic benefits of slots in anodes have been proven and slots which are deep enough to be present through the complete anode cycle present an incremental part of that same benefit [3]. The cost of conversion of an existing slot cutting machine to have deeper slots will have a similar, if not better, business case than a new slot cutting machine project. The expected return on investment is less than two years based on energy savings and potentially less than one year if instead of energy savings there is infrastructure surrounding the project which allows increased aluminium throughput.

The business case calculation will be different for each smelter technology and operational parameters, but the information which needs to be prepared and evaluated are the same. These parameters, along with sample calculations, are as follows:

Estimating reduction in voltage drop in pot (mV) – as an example, based on extrapolation shown in [3], we could roughly estimate 0.25 mV/mm of extra slot depth.

Energy savings in kWh per kg of Al can then be calculated as follows:

Energy saving = (Voltage drop) × (Pot amperage) × (Number of pots) × (hours of production per kg aluminium produced per year).

For a smelter operating at 340 kA with 264 pots and producing 250 000 t/y of aluminium, the energy saving could be estimated as an example:

Energy savings of 50 mm deeper slot for one kg of aluminium produced: $50 \text{ mm} \times 0.00000025 \text{ kV/mm} \times 340000 \text{ A} \times 264 \times 365 \text{ days/y} \times 24 \text{ h/day} / (250\,000\,000 \text{ kg/y}) = 0.04 \text{ kWh/kg of Al produced}$.

Alternately, let us look at using the energy savings to produce more aluminium instead of reducing energy costs. Using a simplistic estimate and an energy consumption of 13 to 15 kWh/kg Al to produce aluminium, the 0.04 kWh/kg Al saved could be converted to a production increase of approximately 0.26 % to 0.30 %. In the case of our example of 250 000 t/y production, this will increase by 750 tonnes. At 2200 US\$/tonne, this will represent an annual revenue increase of 1 650 000 \$.

Another advantage of converting to climb milling, as previously discussed, is the fact that the slots can be kept as narrow as possible. If we look at an anode which is 1500 mm long with two 400 mm deep slots, we have a total cut area of approximately 1.2 m². At a 400 mm depth, we can cut a slot approximately 3 mm to 4 mm narrower with a climb cutting approach. This will equate to $1.2 \text{ m}^2 \times 0.004 \text{ m} = 0.0048 \text{ m}^3$. If we multiply that by a density of 1600 kg/m³ we get a reduction in material removed of 7.68 kg. Approximately 450 kg of carbon anode is consumed per 1000 kg of aluminium produced. Furthermore, if 75 % of the blocks are consumed before removal from the pot, we need $450 \text{ kg} / 0.75 = 600 \text{ kg}$ of anodes to be produced per tonne of aluminium produced. Therefore, in a smelter producing 250 000 tonnes per year, we need 150 000 tonnes of carbon to be produced. At 1 tonne per anode, this would represent 150 000 anodes. If we can increase anode weight by 7.68 kg due to reduced slot width, we will save 1140 anode changes per year.

During a machine conversion from conventional to climb milling, the new drive controllers as well as other optional sensors can be added to introduce Industry 4.0 technologies into the system. These upgrades will monitor and log key parameters such as temperature, number of cycles, feed forces, position, vibration levels and motor amperage including all real time shopfloor dashboards

with alerts and machine utilisation tracking. In addition, remote monitoring and vision technology will be available to enhance the ability to keep a close eye on the ASCM performance and to predict main machine component including blade failure before it occurs. These enhancements target increased uptime and reduced blade consumption and associated operational and maintenance costs.

7. Conclusions

From this paper we can draw up the following conclusions regarding the upgrade of an anode slot cutting operation to deeper and narrower slots:

- The deepening and narrowing of the slots is an industry trend in the quest of optimization of productivity, financial and environmental performance of the aluminium production.
- The practice of sawing the slots in lieu of forming the slots in the anodes allows for the deepest possible slots.
- In order to have the narrowest possible slots, the climb cutting method is preferred over the simpler conventional cutting method.
- Climb cutting is a more challenging method of cutting in the harsh application but the method and technology are now well proven in the industry.
- The conversion of an existing conventional cutting operation can be converted to a climb milling operation which will allow an existing smelter to reach state of the art slot cutting practice while also having an attractive business case for doing so.
- In the process of an upgrade from conventional cutting to climb cutting, further machine enhancements including Industry 4.0 technologies can be incorporated to reduce OPEX costs and increase uptime and productivity of the slot cutting operation, which can optimise machine performance and provide ample maintenance features for predictive fault finding.

8. References

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