Meeting the Requirements of Potline Customers: The Largely Unmet Challenges Set by Barry Welch to Carbon Anode Producers

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Abstract

Barry Welch is well recognized for his contribution to advancing the science and practice of smelting Alumina to Aluminium Metal. He has also made a significant contribution to advancing anode technology, in particular through the work of his students. This is explored further in an accompanying paper. What is probably less well recognized are the significant challenges and opportunities Barry has laid out to anode producers to improve anode quality to meet the increasingly stringent requirements of the Potlines customer. These challenges and opportunities will be outlined and their potential impact described.

Keywords

Barry Welch • Carbon anodes • Aluminum smelting • Improvement • Problems

Introduction

The contribution made by Barry Welch to improving the understanding of the science and practise of smelting alumina to aluminium is well known and covered by other speakers at this Honorary Symposium. Barry has also made very significant contributions to advancing the understanding of the key issues related to improving anode performance with some significant practical achievements along the way. The advances achieved through the students Barry has supervised are covered in a companion paper also presented at this Honorary Symposium [1]. In the present paper, some of Barry's work over the past 10–15 years on helping improve the understanding of the principles underpinning good anode quality and performance are presented. This includes better defining "what good should look like" when it comes to anodes and some ways to get there—either from Barry or suggested by the Authors. The length of the list of topics (See below) covered in this more recent work may be a surprise to those who only associate Barry with reduction cell operations.

In a number of cases, Barry has presented the issues and opportunities he has identified as challenges to anode technologists and manufacturers to basically "lift their game" in order to meet the ever-increasing demands of the potline customer. Indeed one of the challenges he has presented is for anode manufacturers to genuinely see potlines as a customer, and not just the people that take away the rodded anodes (of a quality that producers can "get away with") and replace them with consumed anode butts (And complain on the odd occasions when quality does not meet the current specifications).

As an observation, many of the challenges presented by Barry (which are based on an understanding of the underpinning science and impact on the customer) have not been addressed by the industry, and indeed a significant number appear to have not been given much attention at all, i.e. they have been put in the "too hard basket" or just ignored. In the following, a number of the challenges identified by Barry will be listed and briefly outlined, and in some cases, potential pathways proposed to capture the opportunity or resolve the issue.

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Challenges to Improve Anode Properties and Performance

The following list of challenges presented by Barry to anode carbon technologists and producers has been organised into four broad groupings: Mindset, Quality/performance, Design, and Operations.

a. The necessary mindset of anode manufacturers:
   i. Really recognise that "*Potlines is the customer*" [2] and stop "*blame shifting*". (This is discussed further in Sect. 3)
   ii. Anodes need to be seen as "value add to aluminum production—an essential component that should be designed for performance, not operating convenience" [2].
   iii. Anode producers and potlines should "*have the data that quantifies and proves the most common anode problems*" [3]. (Anode data systems are discussed further in Sect. 4)
   iv. (Continually) Ask "How can anodes help the cells perform better?" [4].
b. The required anode quality and performance:
   i. Barry has consistently and persistently pushed (or in his words, "hammered") the following aspects of anode quality with a strong theme of producing anodes with a low dusting tendency:
      - (Very) Low Sodium in anodes achieved by excellence in butt cleaning [2, 5]. The importance of butt cleanliness is well known, however, it is generally not well monitored. It is now possible to get commercially available devices to do this online, but these are not widely installed. The conventional approach of manual visual observations of butts after fine cleaning (shot-blasting), and maybe daily analysis of crushed butt samples, is insufficient to monitor cleaning effectiveness in a way that reflects the importance of excellence in cleaning butts. Barry's challenge is for a maximum anode sodium level of 200 ppm. In the experience of the Authors, there may only be a handful of smelters that consistently achieve this level, despite it generally being possible to meet this target as long as anodes/butts have not been impregnated with sodium in the potlines. Failure to meet Barry's target can be due to operational (e.g. Operator care and attention) or plant equipment limitations, but it is likely that new approaches to butt cleaning will be required to consistently meet the challenge. Innovation is required.
      - (Very) High and consistent baking temperatures to reduce the differential in reactivity between coked binder pitch and filler coke/butts and to reduce anode carboxy reactivity [2, 5]. There is a limit to how high baking temperatures can be which is set by the onset of significant desulfurisation. Using low-sulfur raw materials is necessary to reduce this limitation. (This is discussed further in Sect. 8.)
      - *High density, but without microcracking that will increase resistivity and affect other properties* [2]. This will give less open porosity which will reduce anode consumption rates [5].
      - *No "Free dust" on anodes sent to Potlines* [2], e.g. eliminate Packing Material Accretions (PMA), damaged anode surfaces (mechanical or slumping damage during baking), particle segregation from anode forming, damaged vertical corners, and packing coke in slots (e.g. Fig. 1). All of these anode defects contribute to dusting in cells but can be fixed, i.e. there is no technical constraint on meeting this challenge from Barry. It requires the determination to not accept these defects as unavoidable and to do the work needed to eliminate them.

   ii. Reduce the electrical resistance of anode connections by, for example, not having any distortion or attack of rod/yoke surfaces that make contact in the electrical circuit [2].

Fig. 1 Examples of free dust on anodes. The cause of all of these defects is known, as are the solutions. Unfortunately, it is still common to see anodes set in cells with these problems. From [2]

iii. Barry recommended a specification for anode quality [5] that is intended for all anodes, not just for samples from selected locations in a baking furnace. A target outcome from the specifications is to have less anode dust and help reduce cell energy consumption through excellent anode quality as "*Producing anodes with raw materials, formulations, and baking conditions that minimize carbon dust will also help cell efficiency gains by eliminating dust generated spikes*" [2]:

Baked apparent density	>1.6 g/cm^3 (with commensurate low open porosity)
Air permeability	<0.5 nPm
Carboxy reactivity residue	>93%
Carboxy reactivity dust	<1%
Air reactivity residue	>80%
Air reactivity dust	<5%
Electrical resistivity	<55 μΩm
Sodium	<200 ppm

This is a tight specification compared to many in use at present, especially considering that it is aimed at every anode sent to potlines, not just a selected sample. While some well-run plants may be able to meet this specification for a period of time, it is felt highly unlikely that this compliance is sustainable especially as baking furnace conditions change over time. Innovation is required to consistently achieve this anode quality standard instead of just writing off the specifications as "impossible".

iv. Barry has also outlined elements of current anode quality that if improved could decrease cell energy consumption by more than 0.4 DCkWh/kgAl [5] through reductions in Gross and Net Carbon Consumption:

- *Desulfurise coke/anodes before setting in the cells (Reduces anode preheat and conversion energy demand, lowers gross carbon).* A relatively simple way of doing this is thermal desulfurisation during calcining; however, this degrades coke quality [6], so innovation will be required to find successful alternatives to reduce sulfur in anodes.
- Reduce carboxy reactivity (Reduce anode preheat and conversion energy demand, reduce net carbon consumption, minimize dust formation, and lower CO_2e emissions).
- *Deliver preheated rodded anodes for setting* (*Reducing cell operating disturbances at the cell, improving Current Efficiency*, will also reduce in-cell anode cracking). (Anode preheating is discussed further in Sect. 7.)

c. Anode design opportunities, including slot details:

i. Anode slots must be optimised based on considerations including changes to the mass transfer induced by bubble flow [2, 3]. Slot size, number, depth, location, orientation, and cut vs formed, all need to be considered so that Current Efficiency and Power Efficiency gains with slots are balanced with mixing, alumina dissolution, and local Perfluorocarbon (PCF) emissions. (Slots are discussed further in Sect. 5.)

ii. The top shape of the anode should be designed to minimise gross carbon consumption, allow the anode to be positioned during setting, retain anode cover to protect from airburn, and act as a surge reservoir for bath to help to avoid flux wash of stubs [2, 3]. (Anode top shape is discussed further in Sect. 6.)

iii. The anode rod assembly needs to be redesigned so that it does not encumber potline operations, enables effective butt cleaning, and reduces rodded assembly resistance [2]. The yoke design should facilitate anode covering and butt cleaning [3] and allow some "flex" to reduce anode cracking and stub bending ("toe-in") but must be able to fit under the cell fume plate during setting (for example, see Fig. 2 below). Barry's view is that there is a need to start with a blank sheet of paper and relook at the anode assembly design including how electrical contact is made with the anode carbon [2].

d. Opportunities to improve anode production operations.

i. "*Preheat anodes prior to setting to reduce the negative impact anode setting has on cell condition and performance*" [2, 5]. (Anode preheating is discussed further in Sect. 7.)

Fig. 2 Example of a yoke design that gives advantages of ease of butt cleaning and some flex to reduce stress on the anode resulting in less butt cracking and stub "toe-in". From [5]

ii. "Better manage baking furnace maintenance so the focus is on maintaining anode quality" [2, 5] and this includes maintaining higher baking temperatures than are commonly used at present to reduce anode dusting. (Anode baking is discussed further in Sect. 8.)

A selection of these topics will now be covered in more detail.

Potlines Is the Customer

In his 2020 TMS Annual meeting Electrode symposium keynote address [2], Barry covered a wide range of topics. One of the challenges he set was for anode producers to make "*Potrooms is the customer*" more than just a slogan by having carbon plants supply rodded anodes "*of such a design and quality that will enable the smelter to approach benchmark standards for gross and net carbon consumption as well as metal quality*" [2]. Sadly, in many plants, it only takes a walk down potlines past anodes arranged ready for setting to see that this anode quality challenge is not always being met. All too often the appearance of these anodes shows examples of defects such as packing coke accretions, inadequate cast iron pour quality including over-pour, carry-over shot on the anode top, damage from anode baking, surface cracking, yoke and rod damage, and misalignment of the rod and/or anodes, and the anode assembly used will probably be a legacy design with little innovation to address recognised issues. These are some of the defects evident from visual inspection of the anode surface, if internal inspection systems that are (finally) being developed for anodes are used, extensive internal cracking in many anodes would be found. There are also likely to be stubholes and stubs that do not meet the current relatively modest rejection criteria but these defects are hidden by cast iron.

These defects would not be present in anodes that were about to be set if Potlines was really recognised as the customer. There are readily known fixes to all of the defects listed (the design opportunities need a bit more work). To some degree, it seems that the acceptable quality is partially defined by reject criteria (Which may or may not reflect the needs of potlines), but also by "what we can get away with before Potlines will complain". To meet Barry's challenge, this must change, anode defects must be seen as failures, not something "to get away with", and the work done to eliminate them.

Having the Data Needed to Quantify Anode Problems (and Guide Problem Solving)

Barry has presented a challenge to anode producers and potlines to "*have the data that quantifies and proves the most common anode problems*" [3]. While process data from green anode manufacture are generally available and well used, data from anode baking and rodding are less available. Anode quality data are usually even sparser, as are anode performance data. In many plants, the only online data available about each anode, beyond visual observations, are limited to green anode properties at forming, baked/rodded anode mass, and low-frequency anode core test results often collected using anode sampling approaches that limit the usability of the data. Anode performance data are commonly restricted to rod + butt mass, and whether (and in some cases, how) an anode failed prematurely in operation.

This scarcity of online data which are critical for efficient and effective anode improvement is disappointing given that the tracking systems designed to deliver these data have been available for the best part of 20 years (e.g. Fig. 3). While some plants have installed these systems and the associated instrumentation such as butts imaging devices, their adoption across the industry has generally been quite limited. There may be site- or company-specific reasons for this; however, a common issue seems to be that these systems are "enablers" and only generate a return on investment when they are used to deliver improvement. This means they fail to meet the accountant's Rate of Return requirements for project approval. So the projects are rejected, despite the tremendous capability of these systems to deliver improvement and financial benefit when the data they deliver are effectively and widely used. In the cases where tracking systems have been approved and installed, it appears to have been an outcome from forward-thinking management and/or a specific target (e.g. Stub repair costs) to provide the benefits side of the project cost/benefit analysis.

Anode tracking systems that extend into potlines (i.e. individual anode performance is measured by cell and stall) have the potential to provide complete transparency about anode quality and performance across the smelter. Integrating anode and cell operating data addresses another of Barry's challenges listed above, i.e. "Blame shifting" about anode performance problems becomes virtually impossible (e.g. Fig. 4).

Anode tracking systems can also substantially improve the capacity of increasingly scarce anode Process Engineers to deliver necessary improvements (and meet more of

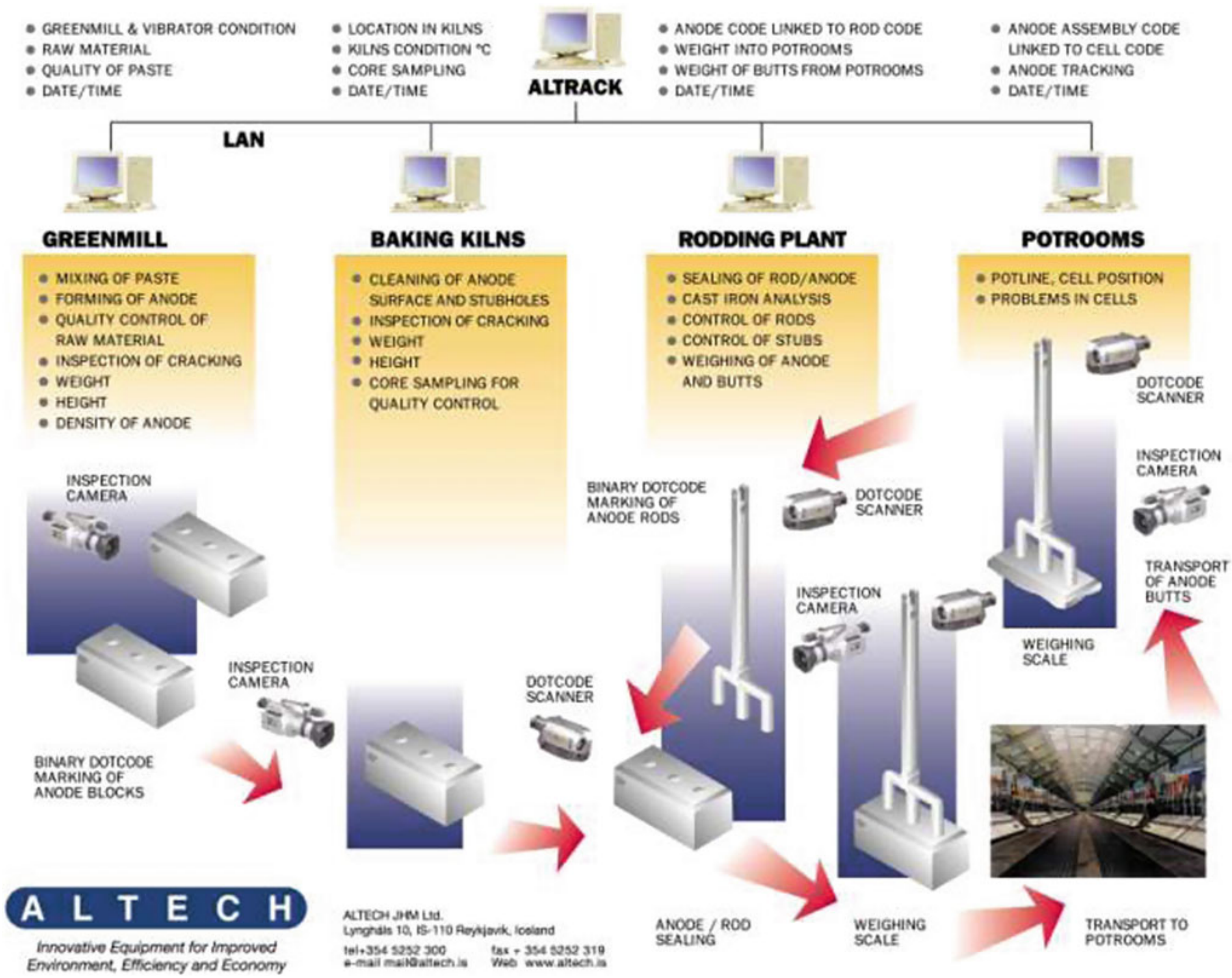

Fig. 3 Schematic example of an early anode tracking system design. From [7]

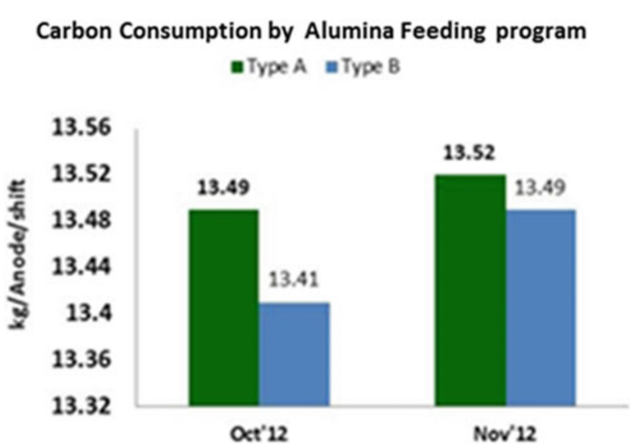

Fig. 4 Example of clarity in understanding the drivers of anode consumption gained through the use of an anode tracking system. In this case, it can be seen that alumina feeding program type B gave a lower anode consumption rate than feeding program type A. Reproduced from [8]

Barry's challenges). Hopefully, this, and the focus driven by "Industry 4.0" initiatives, such as big data analytics, will see anode tracking and online anode measurement systems become accepted as fundamental and necessary components of anode plants in the near future.

Optimising Slot Design

Barry has made it clear for some time now that while slots have delivered significant quantifiable gains in Current Efficiency (CE) and Power Efficiency (PE), they have downsides associated with their impact on electrolyte mixing within the cell. His challenge is presented as "*to optimise the size, depth, and location (Not transverse) of slots to balance gains in CE/PE with the greater spatial variation of mixing which is leading to spikes, alumina dissolution issues, and local PFC evolution*" [2, 3]. This challenge is particularly relevant as a caution to ensure that the reasonably common efforts to maximise slot height, with the maximum set when the slots become "full height" (meaning the slots remain in the anodes for the full anode life), take into account all of the effects slots have on cell operations and performance.

Anode slots were first implemented to disrupt the stress patterns at the base of anodes during setting and thereby reduce thermal shock cracking. They have been very successful at doing this and have reduced restrictions on anode filler coke quality (and hence availability) for anode manufacture by allowing the use of more isotropic cokes in blends. As important as this benefit from slots is, their rapid adoption to an almost universal level across the industry was due to the positive impact they had on CE and PE. Slots provide an escape path from the inter-electrode gap (or Anode-Cathode Distance (ACD)) for the gas bubbles generated during electrolysis, thereby reducing the proportion of the ACD filled with bubbles and lowering cell resistance. The motion of these bubbles through the electrolyte, however, provides the driving force for essential mixing within the cell, so the reduction in bubble volume has reduced this mixing giving rise to the issues identified by Barry.

Higher slots reduce bath movement further and give less of the mixing required to maintain consistent electrolyte concentration and avoid localised variation and alumina dissolution issues [2]. Full height slots maximise this effect as during early anode life the slots are exposed above the bath level and hence minimise any bubble mixing. Barry's challenge is to ensure that all factors, especially those based on an understanding of the science and physics involved, are considered when making changes regarding slots [9]. Rigour is required when assessing the merits of design changes to slots and more fundamental work would seem appropriate to understand and then accommodate the impact of slots on electrolyte mixing.

Barry has indicated a preference for cutting slots rather than forming [2] as the latter impacts anode carbon quality in the vicinity of the slots and this contributes to dust [3]. He also reminds us that all slots increase the anode surface area accessible to attack from electrolytically generated CO_2 and this can generate dust. These factors also need to be considered when making changes to slots.

Redesigning the Anode Top Profile

Barry has demonstrated how anode top design/shape can impact anode and cell performance, challenging the industry to adopt a design *that helps to minimize Gross Carbon, makes positioning of the anode in the cell easier and more effective, and helps retain cover on the anode to provide insulation and reduce air ingress and airburn attack* [2, 3].

Fig. 5 Anode top profile recommended by Barry showing how a surge reservoir for bath overflow is formed; this reduces stub flux wash. From [2]

An example of this design is provided in Fig. 5, showing a profiled top with a sloped area forming a step that gives a flat area around the anode top to retain cover and provide a reservoir on the anode top to help cope with surges of bath from anode motion during anode effect termination. This reduces stub attack and iron in aluminium [2]. While some anode designs already have these features, others have flat tops or chamfers that extend to the anode edges that leave room for improvement.

The recommended design gives better protection to the anode from the improvement in cover, better top shape (less exposed vertical surfaces), and if combined with an optimised (sequential) anode setting pattern has been shown to deliver potential savings in net carbon by limiting airburn and associated dust to $\leq$ 30 kg C/t Al [2]. There would appear to be minimal downsides to adopting an anode profile like that recommended by Barry, and as changes to the top profile are relatively straightforward to make, it appears that this challenge is not difficult to meet. The benefits of easier anode setting, lower net and gross carbon, less dust, and lower iron in metal would seem to make this worthwhile.

Implement Anode Preheating

The setting of "cold" anodes is a major disruption to cell operations and performance, increasing energy consumption and contributing to the formation of spikes associated with the bath freeze that forms on the cold anodes [2, 5]. Barry's challenge is to "preheat" anodes to reduce these impacts.

Ideally, hot anodes (Temperature at about 400 °C to avoid airburn) would be transported straight from the baking furnaces to anode rodding, then immediately delivered in an insulated carrier to the cell for Just In Time (JIT) setting. To make this work, the following would be required:

- Baking furnace operations would need to operate to a very tight drumbeat so that the anode temperature on removal from the furnace is consistent and on target.
- Conveyors and other transfer equipment would need to be able to resist the anode temperatures and be insulated to reduce heat losses.
- Cast Iron thimble details, Cast Iron metal specification including casting temperature, and stub preheating are optimised to ensure a suitably tight stub-carbon connection with the "hot" anodes.
- Although not essential, robotic casting and anode delivery by autonomous vehicles would help to control cycle times and achieve a more consistent anode temperature at the cell.

Meeting Barry's challenge by full implementation of this process means a suitable redesign of the equipment involved and would benefit from locating baking furnace(s) and the rodding room in close proximity to the potlines, but there is potential to implement a degree of preheating using existing equipment (with some modifications to give better heat resistance) now. A high degree of equipment reliability and much greater rigour in scheduling operations /managing cycle times are required but these should be possible in a step toward full implementation. Given the benefits of setting preheated anodes, this challenge would seem to be worth tackling.

Improve Anode Baking

As part of the challenge to reduce dusting, Barry has recommended anode properties that are likely to need higher than generally accepted final baking temperatures. This will require limitations on anode sulfur level to avoid deleterious desulfurisation during baking and require that anode baking furnaces are capable of sustaining these temperatures on an ongoing basis. While ultimately this may require a rethink on how anodes are baked, it should immediately prompt changes to how many existing furnaces are maintained.

Dusting has long been recognised as being important, and yet baking furnace condition is frequently allowed to deteriorate to the point it seriously impacts anode quality and cell performance before the furnace is rebuilt [2]. In the experience of the Authors, inadequate baking furnace condition is the single most common reason for serious dusting excursions in smelters. This indicates that the challenge set by Barry to not allow furnace conditions to increase anode dusting is appropriate.

Baking furnace rebuilds are generally undertaken according to one of three different methods: (1) Continually replacing fluewalls as needed during normal operations, (2) Replacing full section(s) of the furnace according to a tight schedule while maintaining (reduced) furnace operations ("rebuild on the run"), or (3) Shutting the furnace down for a more complete rebuild. Shutting down furnaces tends to be cost-prohibitive if anodes have to be purchased to replace the lost production capacity, but rebuilding on the run is a reasonably common approach. It has the advantages of reducing losses in furnace production, allowing limited changes in refractory details, headwalls can be replaced, and the furnace structure can be re-aligned to correct refractory movement during operation. Rebuilding on the run does require significant forward planning, and once the plans are set, they are not easy to change. If the criteria used to determine the timing of the rebuild prove to be flawed, there is a high likelihood that poor anode quality will result in dusting as a likely outcome. This is not a rare situation in practise.

Rebuilds on the run are commonly planned based on criteria such as visual appearance of the furnace refractories, measurements of deviations in furnace dimensions, data on furnace issues such as blocked/deformed fluewalls, or other criteria such as benchmarks for fluewall life. These criteria are then used to project the furnace refractory life and plan/schedule the rebuild. While anode quality may be considered to some degree, using detailed monitoring of anode quality and performance to set the timing of rebuilds is rarely done, with the outcome mentioned previously—anode quality deteriorates as the furnaces age before the rebuild, and dusting excursions can result.

The challenge set by Barry is to change the way furnaces are maintained so the key criteria for planning are to sustainably supply anodes to potlines that continue to meet a demanding specification including low dusting. Invariably this will mean more furnace maintenance than is done now and will likely drive changes in refractory specifications and baking furnace designs so that acceptable anode quality is consistently achieved for longer periods of time.

While anode sampling, coring, and testing is one approach to getting the data needed to properly project baked anode quality, a better approach is to use a full anode tracking system (see Sect. 4). This will enable anode quality and performance from each baking location within the furnace to be monitored and furnace maintenance to be planned based on statistical projections of the actual anode performance data.

An alternative to this could be to forgo some of the benefits of rebuilds on the run and adopt the continuous fluewall replacement approach, ideally with a tracking system and furnace operating data to help indicate when fluewalls need to be replaced and avoid any deterioration in anode quality.

Meeting Barry's challenge to use delivered anode quality as the key criteria to determine furnace maintenance activities will increase furnace maintenance costs and will likely justify higher quality refractories [5]; however, these can be assessed against the very high cost of anode dusting excursions that are an all too frequent outcome from the current approaches.

Longer term, with tighter criteria for anode quality, revisiting the current concept for anode baking is appropriate.

Conclusions

Barry Welch has outlined numerous science-based challenges and improvement opportunities to anode carbon technologists and producers. A number of these have not been addressed by the industry. Some are simply a matter of adopting a new mindset with existing processes and raw materials, to not accept anode properties or defects that affect anode and cell performance. Others require innovation to meet Barry's challenges. Perhaps one of the most difficult aspects of the challenges from Barry is the question "who is going to do this innovation on carbon anodes"? The answer to this question is compounded by the reportedly relatively short time until inert anodes/cathodes become available, even though it is likely that carbon anodes will continue to prevail for years to come.

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