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ANODE RODDING BASICS

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Abstract

The joint between the rod and carbon anode in aluminium smelters has three primary functional requirements; it must (i) provide an adequate mechanical, thermal, and electrical connection, (ii) be able to be re-processed cost effectively, and (iii) withstand the extreme process conditions. There are also two further important performance requirements; (iv) the joint materials must not adversely affect Occupational Health, Safety and Environment (OHS&E) conditions or metal purity, and finally (v) the manufacture, maintenance and operation of the joint should be managed holistically to minimize smelter costs. To achieve these requirements, the basic production steps in anode rodding must be done to an acceptable standard, all of the time. Not meeting these standards has a detrimental impact on smelter performance and costs.

This paper first outlines acceptable standards for the basic steps of rodding anodes, and then reviews the state of the art, challenges, opportunities and future directions for the rod-anode connection.

Introduction

The anode rod fleet for a modern smelter often consists of 10,000-20,000 units with a financial investment in the order of US$20 million. It is important that operational staff understand why care must be taken in the anode rodding process to deliver the optimal financial outcome for the overall business. If allowed to deteriorate, a poor quality anode rod fleet can easily consume an additional 50-70 mV above its intended design voltage drop [1]. This will result in increased smelter power costs of, for example, in the order of US$4 million per year for a modern smelter of 500,000 tonnes per year production [2]. In addition to the potential for lower power consumption, operational and maintenance staff have the opportunity to influence the environmental performance of a smelter by minimizing the waste/by-product streams generated by rodding room processes. As Taylor summarised [3], there is no conflict of priorities between safety, costs, production and good process and asset management (in rodding operations), it is simply the lack of feedback.

The authors have had the opportunity to independently review the operation of numerous rodding rooms. It has been consistently observed that many of the basic anode rodding production steps are not done well, to the detriment of anode and cell performance. The following discussion will outline the important elements of the major process steps, the deficiencies often observed, and the minimum standards that should be met, all of the time, to maximise anode and cell performance. More specifically, the focus of this paper is on improving the quality of the connection between the rod and the carbon anode in the cell.

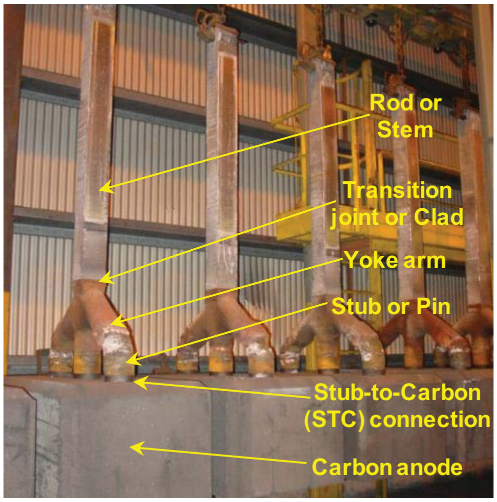

Figure 1. Rodded anode assemblies ready to be delivered to reduction lines.

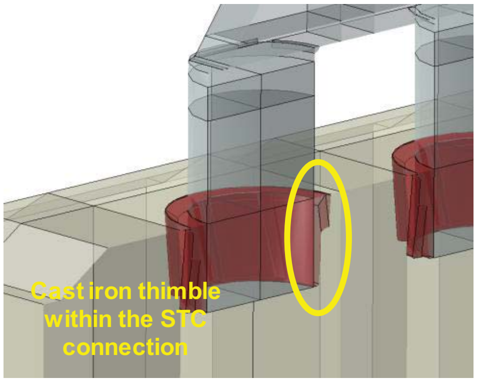

Figure 2. Close-up highlighting the cast iron thimble within the Stub-to-Carbon (STC) connection.

Basic Steps of Rodding Anodes and State of the Art

Cleaning of Returned Carbon Anode Butts

The primary purpose of the initial 'coarse' butt cleaning step is to remove as much of the cover material from the top of the spent anode butt without fracturing the butt carbon. When doing this, it is essential to not unduly stress the anode rod assembly (see Figure 1 for suggested anode assembly nomenclature), which can easily occur by improper design or inadequate maintenance of the equipment. Brutally large forces are applied to the cover material in order to remove it from the anode butt. It is especially important to ensure that these forces are applied as intended and not directed onto the assembly, to avoid bending the anode rod, stressing the clad, or other physical damage. The performance of the coarse cleaning stage is greatly affected by the level of cover material on the butts. In addition to adversely impacting coarse cleaning operation and effectiveness, high cover also overheats and damages the rod assembly by increasing 'toe-in' (or cowboy effect) of stubs, corrosion of the yoke arms, cumulative clad damage, and deformation of the yoke. As a rule of thumb, cover height on butts should be low enough to allow a gloved hand to be inserted between the underside of the yoke arm and the cover, Figure 3. This allows air to circulate around the yoke arms to provide a cooling effect, remembering that one of the design functions of the yoke is to shed heat from the process before it gets to the clad and rod.

Figure 3. Well maintained end of cycle cover levels, not engulfing the yoke arms.

Fine Cleaning of Returned Carbon Anode Butts

Fine cleaning (usually by shotblasting) of the coarse cleaned butt is required to achieve the desired low levels of sodium in the anode butts stream returned to the paste plant. It is well known that high sodium in butts severely affects subsequent anode reactivity and baking furnace refractory life. The fine cleaning step should also effectively clean the top of the cast iron thimble, Figure 2, from retained cover material, reducing contamination of the stripped cast iron. An excellent example of a well cleaned butt is shown in Figure 4.

Figure 4. Excellent example of a well cleaned carbon anode butt.

Stripping of Spent Carbon Anode Butt Material and Cast Iron

The carbon butt material can be stripped from the rod in a separate step prior to the removal of the cast iron thimbles, although it is more common in modern smelters with 'in-line' stub configurations to combine both carbon and cast iron removal in one stage. The cast iron is then magnetically separated from the carbon in subsequent processing. When stripping butt carbon independently, it is important to minimise the amount of carbon adhering to the cast iron thimbles, as this has to be removed during thimble cleaning otherwise it will contaminate the cast iron melting furnace charge. In the process of removing the cast iron thimbles, whether independently or with the butt material, it is essential that the upper surface of the thimble is correctly, and tightly, restrained to resist the large forces applied by the stripping press. Regular and dimensionally accurate maintenance of the stripping press is required in order to achieve not only optimum stripping efficiency, but also to ensure that unbalanced stripping forces do not load the anode rod and cause physical damage. For example, if the 'rockbits' of a butt and thimble stripping press are not correctly (concentrically) located relative to the stub centers, the unbalanced force will very rapidly cause stub and/or yoke arm distortion to occur for the entire anode rod fleet within a single rodding cycle. This type of systematic damage has serious adverse effects on subsequent rodding stages and can be very costly to correct. Other defects often encountered at butt and/or thimble stripping include; (i) cast iron pieces left adhering to the stubs after thimble stripping, Figure 5; if not removed, these impact alignment of the Stub-to-Carbon (STC) connection and hence increase mV losses – see later, and (ii) excessive cast iron stripped with the butt material – this can overload the magnets and increase the amount of cast iron in the recycle butt carbon stream. A further problem is the stripping of small pieces of cast iron attached to larger pieces of butt material. These small pieces are difficult to remove with magnets, and in addition to increasing iron in butts, can also damage any cutting tools used to cut anode slots, clean stubholes or cut locking mechanisms within the stubholes.

Figure 5. Cast iron adhered to stub after thimble stripping process.

Cleaning of Cast Iron Thimbles

There are two main reasons that cast iron thimbles are cleaned before being recycled; (i) primarily to remove adhering bath, which contains large quantities of both sulphur and sodium, and the iron sulphide scale on the thimbles – sulphur is unwanted in the cast iron melt and sodium will attack the refractory lining of the induction melting furnaces, and (ii) to remove any of the carbon adhering to the thimbles – if not removed, this carbon contributes to contamination of the cast iron, especially with sulphur, and generates excessive slag during preparation of the cast iron melt. Excessive slag will adversely affect the ability of furnace operators to properly add and mix alloy additions to the melt (and hence to control cast iron chemistry) and will cause additional challenges for pouring of the thimbles. Furthermore, excessive slag production generates a greater quantity of a difficult to process waste stream from the rodding room. Cast iron thimbles must be cleaned prior to recycling – it is false economy to charge uncleaned thimbles.

Cleaning of Stubs

Routine cleaning of stubs is not always performed by smelters, with some smelters having opted to not include a stub cleaning stage as part of their normal production equipment. Where stub cleaning is undertaken it is most often by steel shot blasting. Some smelters have employed rotating wire brush systems to clean the stub surfaces. The performance advantages of stub cleaning will be discussed in conjunction with graphite coating of stubs later in this paper.

Anode Rod Straightening

It is unfortunately common that hot (i.e. at the end of cycle or rota) anode rods are easily over-stressed and bent if the cover material around the spent anode butt is not sufficiently broken by jack-hammering to release the butt prior to removal from the reduction cell. This is further compounded by the presence of high cover levels within the cell. If the bend in the anode rod is not corrected before being cast into a new anode, the cell current distribution will be adversely affected. This will increase cell noise because the base of the anode will be out of alignment compared to the other anodes in the cell [4]. An estimated voltage penalty for this defect is not available at present, but is expected to be quite significant. Some smelters experience such significant rod bend that they must pre-straighten the rods attached to spent anode butts (with cover still in place) prior to any processing steps in the rodding room. It is more common, however, for the rod straightening press to be located in the process after the butt and thimble stripping press(es), but prior to the anode rod inspection station. Ensuring that the anode rod straightening occurs before the unit is inspected and potentially rejected for repairs will ensure that any subsequent repairs are done in relation to a correctly straightened anode rod. The best way to avoid bent rods on anodes is to remove anode butts from the cells correctly without using the rod as a lever, however given that a proportion of rods are normally bent when they arrive in the rodding room, it is essential that rod straightening is effective so that all anode rods sent to reduction lines after rodding are straight.

Inspection and Rejection of Anode Rods

This is the most influential step in the maintenance of the anode rod fleet. There are essentially three levels of inspection possible:

i. The most basic is **manual inspection** with the use of gauges to assess the geometry of the anode rod and stubs for subsequent fitment into the carbon anode. Whilst most smelters will have developed various physical inspection gauges for the required standards, the use of these gauges is a highly subjective operation. The decision making process by the operator on whether to reject a rod for repair will be heavily (but inappropriately) influenced by the present frequency of rod/stub damage, repair quotas, available production time, rod assembly/rodded anode stock levels, and rod repair cost pressures.
ii. Automated stub inspection equipment has been used since the late 1990s in a **semi-automated** rejection mode, whereby the system flags a sub-standard anode rod, but the operator makes the final decision on whether it is sent to repair by applying the appropriate coding to the anode rod unit. Aside from the elimination of manual gauges and helping to keep the operator from the vicinity of the anode rod, thereby reducing the risk of injuries, the use of automated stub inspection offers a significant leap forward by accumulating valuable anode rod fleet geometry data to determine the mechanism by which stubs, yokes and rods are deteriorating, and at what rate. This enables a greater degree of planning and budgeting in fleet maintenance.
iii. The components exist to assemble a **fully automated** rod/stub inspection, coding and rejection system to eliminate the subjectivity (and likely boredom!) associated with the testing and decision making by the operator during the rod inspection and rejection process. In addition to rejecting anode rods for traditional geometric defects, a fully automated system makes it possible to reject rods for repair based on the overall condition of the anode rod with regard to all of the stubs working in parallel, something that is not intuitive to operators. For example, one stub on an older assembly may be flagged for rejection, but the new stub will be shorter than the remaining stubs and result in a significant cast iron 'pancake' under the new stub. A fully automated system can calculate the net effect of all repair possibilities to any given anode rod and calculate the most cost effective set of repairs to perform to that anode rod based on overall performance.

Irrespective of what method is used to inspect rod condition, the essential requirement is that rods that do not meet standards are rejected for repair and not allowed to "go around one more time". Rejection standards must be complied with – otherwise the rod fleet condition becomes an unknown. Whether the rejection standards are appropriate or not is a different question, however the experience of the authors is that from an overall business value perspective, rejection standards tend to be too lax rather than too tight. The importance of properly coding rejects should not be underestimated. A great deal of staff time and rod repair budgets can be consumed in smelters by not having clear rejection codes, not applying them consistently, or not communicating the definition of the codes clearly to the rod repairer.

Maintenance of Anode Rods

Firstly, it must be said that it is of paramount financial importance to the smelter that the rodding room takes full responsibility for ensuring that only the requested repairs are undertaken by the rod repairer and that these repairs are completed to the required quality standards. These standards must be clearly specified and audited against by the smelter. Rod repairs can be undertaken both internally and externally – and there are benefits to both. Internal rod repair facilities can be cost effective if managed and reviewed with rigor, otherwise there is some virtue in the customer-supplier relationship with an external rod repair contractor, but this arrangement will leave the smelter exposed to the contractor's profit margin and price fluctuations. As mentioned in the previous section, one of the most underappreciated aspects of proper maintenance is to ensure that the coding of rejects is consistent and that both the rodding room and the rod repairer have exactly the same interpretation of the work to be performed. Smelters utilising external repair contractors can maintain excellent cost control and repair quality if they properly allocate resources to oversee this work. A full time role is justified to properly manage a US$20m asset with an annual maintenance budget of typically US$4m or more.

Graphite Coating (and Drying) of Stubs

Nearly all smelters coat stubs with a graphite based solution or dry graphite based powder to inhibit cast iron adhering to the stubs. These pieces of sticking cast iron make it more difficult to remove the next thimble cast on the stub and are likely to prevent the stub from being located properly into the new anode, resulting in a sub-optimal thimble and an increase in cell mV losses. Many smelters using graphite solutions have moved away from organic spirit based solvents towards water based solutions to reduce the OHS&E risks associated with exposure to the organic liquids and their vapours. The most critical safety related aspect of using water based graphite solutions is to ensure that the coated stubs are fully dried before casting to prevent steam explosions when the molten cast iron contacts the coated stub. This is especially important when rods have been transported and/or stored outside, as stubs are likely to have a coating of surface rust which is known to trap moisture. Some smelters experience large variation in coating consistency when using water based graphite solutions, finding that additional effort is required to ensure that solution mixing and density are maintained to achieve adequate results. To the best of the authors' knowledge, there has not been a scientific study of the impact of cleaning and graphite coating of the stubs on the performance of the STC connection. Based on industry experience, however, a saving of 5 mV is reasonable for well cleaned and coated stubs and has been reported by several smelters. The mechanism for the improvement in contact resistance is likely to be primarily due to the removal of resistive oxides (scale) and bath contamination from the stubs, and avoiding the misalignment of stubs in stubholes due to sticking pieces of cast iron. In the experience of the authors, graphite coating is a necessary step in the rod preparation process to avoid cast iron sticking to the stubs. The quality of the graphite coating can be tested by rubbing a white cloth rag on the coated stub – a black deposit should be left on the rag, not a grey 'smear'.

Inspection and Cleaning of the Anode Stubholes

To achieve a high quality STC connection it is essential that stubholes are consistent and meet quality standards. It is often observed that loose packing coke is left in the stubholes of anodes sent to be cast. Any material retained in the stubholes will cause the whole anode rod to sit up in the holes higher than designed. When stubs sit up high, a large amount of cast iron penetrates underneath the stubs, increasing mV losses [1] and cast iron usage. Furthermore, a very large cast iron thimble will be more difficult to remove at the stripping press. It is important that the green and baked anode production processes maintain the integrity of the cast iron mechanical locking mechanism built into the stubholes (flutes, indentations or 'dogs', rings, groves, tapers etc.). Damage to the locking mechanism will increase mV losses at the STC connection and increase the risk of an anode falling from a rod – a very hazardous event. For these reasons it is very important that only clean and undamaged stubholes are presented for rodding.

Alignment of Rod Assembly to the Carbon Anode

The primary purpose of aligning the rod correctly in the anode block should be to ensure that the rod contact zone (with the anode beam on the cell) is perpendicular to the base of the anode to minimize cell noise [4]. A secondary, but still important purpose is to ensure that the stubs are placed centrally within the stubholes to minimize the variation in cast iron thimble thickness around the stubs, Figure 6. It has been observed in laboratory and plant testing [1] that the thickness of the cast iron thimble influences the STC connection quality and hence will affect the current distribution from the anode rod assembly to the anode block. Where anode rod to block alignment devices are used during anode rodding set-up, special attention should be paid to the locating stops, checking regularly that any wear is within the acceptable tolerance to avoid systematic misalignment of the rod/stubs relative to the anode block. In smelters that do not have anode rod to block alignment devices, the authors strongly recommend that they be installed, as their experience is clear that the gains in cell operation with anodes rodded with the locating devices will far outweigh the capital, operating and maintenance expense incurred with the locators.

Figure 6. Off-centre position of stub in stub hole and resultant uneven cast iron thimble thickness.

Preparation of the Cast Iron Melt

Historically there has been little scientific input into the specification of cast iron used specifically for anode rodding purposes. The general trend is to target the production of a predominantly grey cast iron and to maintain the composition within specifications. Grey cast iron is preferred as it has more favorable and predictable thermal and mechanical properties than the alternative white cast iron. Experience and experimentation has shown that the following cast iron composition is effective: Carbon Equivalent (CEV) 4.3-4.7 %, carbon (C) 3.4-3.6 %, silicon (Si) 2.6-3.0 %, no phosphorous (P) addition, sulphur (S) <0.10 %, manganese (Mn) in proportion to S levels, but <1 %. Other, independent studies have arrived at similar optimal cast iron specifications for anode rodding [5][6]. Phosphorous is still added by a decreasing number of smelters in order to increase molten cast iron fluidity, but it has been omitted here as it accumulates in the cell and reduces current efficiency if thimbles are attacked by bath. The multi-valent properties of P means that it can form a RedOx cycle in the bath, continually being reduced at the cathode and oxidized at the anode, consuming power without making metal. In addition, experience has shown that P does not give a marked improvement in fluidity to the recommended cast iron composition at temperatures above 1350 °C. However, high P cast iron does have specific thermal-mechanical properties that can be exploited for improved STC connection performance if, and only if, the anode integrity remains intact and the cast iron is not exposed to the bath. Sulphur is generally considered an unwanted impurity that disrupts the cast iron composition, structure, and performance; in addition, any SO_2 releases from the induction furnaces can be an OHS&E risk, especially during deslagging. Excessively high S levels result in the formation of white cast iron, even when the CEV value indicates the structure should be grey. The cleaning of thimbles before recycling to remove anode carbon stripped with the cast iron is essential to control S levels, and good quality foundry carbon raiser (and/or silicon carbide) should always be used to increase cast iron carbon levels, never use anode coke. Manganese is predominantly added to help control S levels in the cast iron at a ratio of about $Mn = 1.7(S) + 0.4$. Once the cast iron composition specification has been set, it is essential that operators only pour metal from the induction furnaces into the anode casting ladles that is within specification (composition and temperature). Cast iron preparation practices vary, but a typical approach is to initially add bags of pre-weighed quantities of carbon raiser, ferro-silicon (or silicon carbide), and ferro-manganese to an induction furnace charge of thimbles. After melting and deslagging the charge, and the correct temperature for analysis is reached, the metal composition (CEV, C & Si) is tested using a commercial thermal analyser. Further alloying additions are then made as required to get the metal towards specification. This cycle is repeated until the metal is within the target composition tolerance. The metal is then brought to the target temperature (e.g. 1450-1475 ^{o}C), skimmed, and poured into a casting ladle. To ensure consistent cast iron composition is achieved, several samples should be taken from different casts each shift for analysis in the plant laboratory to cross check and maintain the calibration of the thermal analyser. Steel such as cut off stubs are often used to make up cast iron losses. This is usually cheaper than using pig-iron for make-up, but does mean that achieving the target composition is slightly more difficult.

Pouring of the Cast Iron Thimbles

The target should be to fill the thimbles completely, with no underpours or cast iron spillage on the top surface of the carbon anode. Underpours increase mV losses at the STC connection and affect heat flow up the stub/rod. If not removed, cast iron spilled on the anode will inevitably find its way into the aluminium metal produced, if not during the initial cycle, then very likely when the cover material is subsequently removed in the rodding room for reprocessing. As discussed in the previous section, it is usual to specify grey cast iron for the anode rodding process which will shrink upon solidification and cooling, resulting in an airgap between the outer surface of the cast iron thimble and the stubhole wall. For electrical and thermal conduction, this airgap is problematic and the topic of much discussion [1,2][5-12]. However, from a mechanical connection standpoint, the air gap is critical in preventing anode carbon cracking late in the anode cycle during cell operations. The airgap absorbs the higher relative thermal expansion of the stub and thimble within the stubhole, thereby avoiding excessive stresses that would otherwise crack the anode. The width of the airgap is, therefore, critical to the electrical, thermal, and physical performance of the rodded anode. It is important to keep factors that influence the airgap, such as cast iron composition, pouring temperature, stub/stubhole preheat temperature and cast iron thickness, as consistent as possible to maintain low variation in the STC connection. Production pressures exist in all rodding rooms to cast more units from a single ladle of cast iron. This will result in cast iron being poured that is too cold. A low cast iron temperature can result in ‘cold shuts’ forming (incomplete filling) and the resultant thimble will have large regions that will not carry current between the stub and the stubhole wall, e.g. Figure 7. The formation of cold shuts is highly undesirable and will result in an increased STC voltage drop. Casting anodes with a stub hard against the side of a stubhole will also cause problems similar to cold shuts. In severe cases, cold shuts may potentially affect the mechanical integrity of the anode assembly.

Stub Protection Collars

Stub collars are used by some plants to protect the stubs from attack from bath (‘flux wash’) in the cells. They can be either preformed solid carbon or refractory collars that interlock around the stub, or paste placed inside a metal or cardboard collar around the stubs that then bakes out during anode operation to form the protective layer. Collars may allow plants to operate with thinner butts without excessive flux wash, but at least some of the collar material remaining on the butts tends to end up with the butt bath that is recycled to the cells as anode cover, thereby increasing the amount of carbon in the cover material and ultimately the electrolyte. This is deleterious to cell performance and for this reason, together with the cost of the collars, most plants do not use stub protection beyond normal anode cover. They consider a better approach to avoiding flux wash is to address the root causes: variation in bath height in the cells and variation in rodded anode quality, including the STC connection.

Figure 7. A ‘cold shut’ in a cast iron thimble.

Anode Rod Identification and Tracking Systems

Some companies now have each rod individually coded in a machine readable code such as dot codes, bar codes or RF tags. This can be used to (i) generate data for anode mass balancing (weighing rodded anodes going to reduction lines and the butt on the same rod returning from reduction lines so that anode consumption rates can be continuously monitored instead of just being month end calculations), (ii) integrate full anode tracking systems into the reduction lines, and (iii) to provide the usage history and maintenance record of a given anode rod to better manage and forecast rod repair requirements. Whilst the primary tracking method may employ dot codes, bar codes or RF tags, they should be complimented with corresponding alpha-numeric codes to aid human inspection to enable efficient trials and monitoring/audit campaigns to be undertaken.

Challenges in Practical Application of the Principles

As discussed, the costs for maintaining the anode rod fleet are not insignificant even under stable operations; it is therefore crucial that a proper customer-supplier relationship is established and maintained between reduction lines and the rodding room [3]. It has been observed in many smelters the significant impact to both the rod repair budget and workload of rodding staff when problems such as high bath levels, anode cracking, or airburn events occur within reduction lines. Whilst it is usual for the event to trigger discussions between carbon and reduction departments, the attributed cost of such events is often not well determined and fed back to the reduction lines – and if done, it is usually only months after the event. This can be rectified by properly allocating staff to continuous monitoring and forecasting of rod rejection rates, repair trends and associated budget expected for the coming months, remembering that a nominal budget of US$4 million per year (or more) can very quickly quadruple as a result of the events described above.

Accounting systems that clearly identify the cost of rod repairs in the carbon plant budget, rather than directly attributing the cost to reduction lines, do not help in getting the required focus on rod damage. A process focus is required in the carbon plant and reduction lines – including recognition of the need to incur costs in 'my' budget to achieve gains elsewhere in the plant as the net result is good business value for the smelter. This requires a management approach (and accounting/staff reward systems) that are not always evident in the industry.

The most basic function of anode rod inspection and rejection is to prevent a situation where the anode rod will not fit into the stubholes of a new anode, as would be the case for a rod containing either severe toe-in, missing stubs or a retained thimble on one or more stubs. Manual inspection leads to substantial variation. It is impossible for operators to relate a combination of defects across the entire anode rod with the subsequent collective performance penalty in the reduction cell. Smelters without automated stub inspection systems will never be able to achieve an economic minimum operating position for maintenance of the anode rod fleet.

Opportunities and Future Directions

The highly mechanized nature of the rodding room lends itself far better to automation than it does to manual operation. The full range of equipment required to realise this vision is available from multiple vendors globally. A holistic approach must be taken to assess the condition of the anode rod fleet, determine the most economical combination of repairs for each anode rod (considering the effect of all STC connections in parallel for the anode rod) to return the fleet to service with minimum forecast STC penalty, having spent the minimum amount on maintenance of the fleet. The effort requires quantification of STC penalties for various defects and fit-up issues [1] as well as economic inputs such as forecast power price. In all rodding rooms inspected, none have yet been able to take and successfully implement a holistic approach, though many are credibly on that path.

Regarding anode, anode assembly, cell and anode butt tracking – all of the systems to enable tracking exist today and a number of smelters have attempted this with varying degrees of success. It is more important to have a clearly defined purpose and business case around the need to track first and determine the appropriate equipment subsequently. If the purpose is not well defined (and valued) by the smelter then the equipment, however capable, will not be maintained and the whole system will fail.

Utilising stub inspection, anode rod and anode stubhole inspection it will be possible to produce bespoke stubholes – cut to order to suit individual anode rods, achieving perfect cast iron proportions (depth and diameter) every time. This will be coupled with stub and stubhole preheating to control the shrinkage of the cast iron and subsequent formation of airgap. Pouring the exact amount of cast iron can be achieved robotically because the exact volume of cast required can be calculated in every case [13].

Feedback of the fleet condition (in as close to real time as possible) to the reduction lines will result in improved attention to the performance of the rod fleet throughout the reduction process. In time, technology will exist to test each rodded anode assembly and quantify the expected in-cell performance prior to the assembly leaving the rodding room.

Beyond the rodding room, technologies are developing to enable driverless anode transport vehicles, eluded to by Sadler [13] and Grunspan [14]. Certainly, autonomous hot metal carriers have already been demonstrated [15].

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