SELECTION OF COPPER ELECTROWINNING HARVESTING METHODS AND IMPACTS ON COPPER PRODUCT QUALITY.

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ABSTRACT

The methods of harvesting copper from stainless steel mother plates has been investigated from fundamental and operational experience perspectives. At least five different harvesting techniques have been identified that have different effects on product quality, current efficiency, current distribution, growth morphology and ease of stripping. Each method is examined from fundamental principles to understand what occurs during the harvesting process and why the particular effects are manifested. Experience from plants operating the harvesting method is provided to show that the fundamental understanding is relevant. Best practice harvesting method and harvesting management are described.

KEYWORDS

Copper, electrowinning, stainless steel cathode, product quality, harvesting method,

INTRODUCTION

The method of harvesting copper deposited on stainless steel cathodes during electrowinning operations has a profound effect on the copper quality. A number of harvesting methods have been, and are being used, in the industry with various degrees of impact on the deposit quality. The quality parameters that are usually measured are:

- Sulphur
- Lead
- Ease of stripping the copper
- Presence of nodules or rough surface texture

In all cases considered in this paper, there is an assumption that the harvesting is conducted live. This infers that the current is not reduced during harvesting but kept at the normal level for that particular plant. One of the principal reasons for doing live harvesting is to protect the anodes and cathodes from damage if no current is flowing. In copper electro-refining the copper anode and copper deposit on the cathode leach very slowly in electrolyte, and do not set up a galvanic couple. In electrowinning however the copper on the cathode and the lead anode do set up a reverse voltage. The resultant reverse current flow can have dramatic impacts on electrodes and copper product:

- Copper is dissolved from the cathode creating a porous structure that contains electrolyte and lead flake. These contaminants create off specification product.
- Once the copper is dissolved from the cathode, the underlying stainless steel mother plate is subject to impressed current corrosion leading to pitting and destruction of the plate as a viable deposition platform.
- The anodes are subject to the same reverse current leading to changes in corrosion product chemistry and morphology. The resultant spalling of the lead dioxide layer into the cell contributes to high lead in cathode.

The current that would be applied to the cathodes removed for harvesting is redistributed to the other local cathodes (and anodes) raising their operating current density for the entire period that the cathodes are out of the cell. It is the effects of the extra operating current, the absolute current density on the remaining cathodes, the timing of when it is applied in the growth cycle and the time for which it is applied, which has significant impacts on the deposit quality. An excellent recent paper by Blackett and Nicol (2010) provides the basis for modelling the current re-distribution and the propagation along the cell row during harvesting.

The major production aspect of EW harvesting is the efficiency and productivity of the materials handling system for the harvested and returned stripped cathodes. This productivity includes not only the crane(s) and stripping machine(s) but also the human interactions with these units. Some alternate management practices have been implemented that have increased personnel productivity by providing opportunities for internal personal motivations to take effect without external impetus.

EW TANKHOUSE LAYOUT

In order to provide a coherent description the following EW layout is assumed for a relatively simple plant. Other much larger operations can be sub-divided into this type of simple block. Figure 1 shows the layout of two cell aisles each with three blocks of cells. The harvesting is assumed to be on a six day cycle to allow the operating sequence to be described more simply. Figure 2 provides three alternative cathode numbering systems that relate to the method of their harvesting.

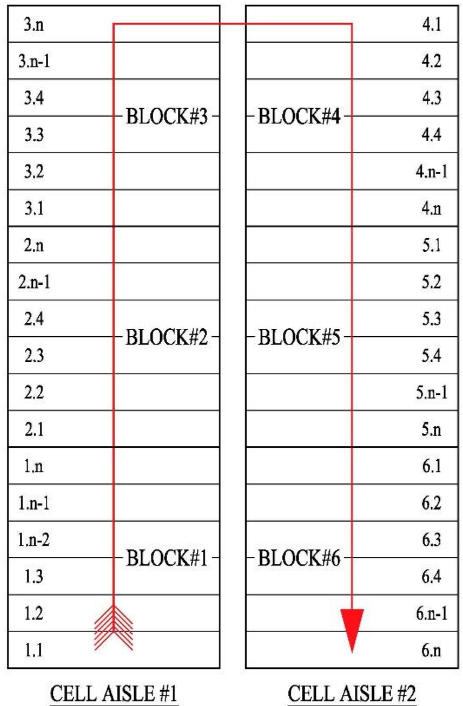

Figure 1 - Cell House Overall Arrangement.

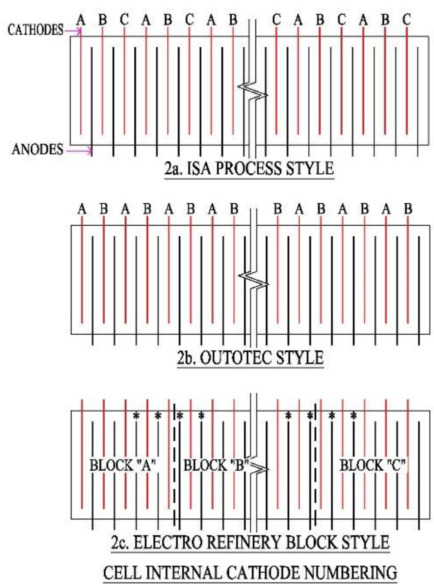

Figure 2 - Alternative Cathode numbering: 2a every third cathode, 2b every second cathode, 2c three blocks of cathodes.

ALTERNATE METHODS OF CATHODE HARVESTING

A number of alternate methods of cathode harvesting have been identified as in use by the industry. Some are direct copies of starter sheet operations, others are a hybrid of starter sheet and stainless cathode methods. Others have elements of electro-refining ‘dead’ harvesting, while two methods have been developed especially for use with stainless steel cathodes.

‘Every Third’ Method

In this method of harvesting every third cathode is removed from each cell. It is the method from the XT ISAKIDD tankhouse group and recommended in all installations of their technology. Firstly the “A” cathodes are harvested (Figure 2a) and the stripped cathodes are replaced. The “A” cathodes are removed from every cell in sequence in the tankhouse in a period of two days. Secondly the “B” cathodes from every cell in the tankhouse are similarly harvested and stripped cathodes replaced; also over a period of two days. Lastly the “C” cathodes are harvested and stripped cathodes replaced from the whole tankhouse. In this method, the harvesting proceeds in three separate passes around the entire tankhouse each pass taking two days

The current density and temporal pattern on the cathodes is relatively benign:

- The “A” cathodes are subject to 150% of nominal current density for two periods while the “B” and “C” cathodes are harvested. The two periods are separated by two days with the first occurring two days after first deposition with a time of approximately ten minutes each.
- The “B” cathodes are subject to 150% current density for two periods while the “C” and “A” cathodes are harvested. The two periods are separated by two days and last approximately ten minutes each.
- The “C” cathodes are subject to 150% current density for two periods while the “A” and “B” cathodes are harvested. The two periods are separated by two days and last approximately ten minutes each.

There are a large number of operations in the industry using this method of harvesting.

‘Every Second’ Method

In this method of harvesting every second cathode is removed from each cell. It is the method from OUTOTEC and used in all installations of their technology. Firstly the “A” cathodes are harvested (Figure 2b) and the stripped cathodes are replaced. The “A” cathodes are removed from every cell in the tankhouse in a period of three days. Secondly the “B” cathodes from every cell in the tankhouse are harvested and stripped cathodes replaced; also over a period of three days. In this method, the harvesting proceeds in two separate passes around the entire tankhouse each pass taking three days

The current density and temporal pattern on the cathodes are more severe than the ‘every third’ method with:

- The “A” cathodes are subject to 200% current density for one period while the “B” cathodes are harvested. The period lasts normally ten to twenty minutes, but can be up to two hours, depending on the harvesting management; and occurs three days after first deposition.
- The “B” cathodes are subject to 200% current density for one period while the “A” cathodes are harvested. The period lasts ten to twenty minutes, but again can be up to one to two hours; and occurs three days after first deposition.

There are around four or five ‘Every Second’ operations in the industry, and one other at BHAS (D. J. Readett, personal communication, November 5th 2013) using this method of harvesting.

Starter Sheet Style

In this method all cathodes are harvested from each cell before moving to the next cell. Firstly the “A” cathodes are harvested (Figure 2a) and the stripped cathodes are replaced. Secondly the “B” cathodes from the same cell are harvested and stripped cathodes replaced. Lastly the “C” cathodes are harvested and stripped cathodes replaced. The harvesting then proceeds to the next cell along the cell aisle; until the block of cells for the day is completed

The current density and temporal pattern on the cathodes are more extreme with:

- The “A” cathodes are subject to 150% current density for two periods while the “B” and “C” cathodes are harvested. The two periods are very soon after the stripped cathodes are replaced in the cell; generally within ten minutes of each other; and for about ten minutes.
- The “B” cathodes are subject to 150% current density for two periods while the “C” and “A” cathodes are harvested. The two periods are separated by the full six day growth cycle, with the first very soon after the stripped cathodes are replaced in the cell (“C” cathode harvesting); while the second is at the end of the “B” cathode growth when the “A” cathodes are stripped. The time span for the high current density is about ten minutes each.
- The “C” cathodes are subject to 150% current density for two periods while the “A” and “B” cathodes are harvested. The two periods are at the end of the “C” cathode growth cycle; generally within ten minutes of each other; and for periods of ten minutes.

At least three operations have been investigated that have used this style of harvesting; although more are likely to be doing so.

Modified Starter Sheet Style

The modified starter sheet operation is similar to a mixture of the starter sheet style and the Every Third method. In this method of harvesting the cathodes are removed in sequence from each cell; in the block of cell to be harvested for the day. Firstly the “A” cathodes are harvested (Figure 2a) and the stripped cathodes are replaced. The harvest then moves to the next cell in the block; and so on until the “A” cathodes have been harvested in the day’s block. Secondly the “B” cathodes are harvested and stripped cathodes replaced; once again proceeding until all the “B” cathodes in the day’s block of cells are harvested. Lastly the “C” cathodes are harvested and stripped cathodes replaced. The “C” cathode harvesting then proceeds to the next cell along the cell line; until the block of cells to be harvested for the day are completed.

The currently density and temporal pattern on the cathodes is still relatively extreme for the “A” and “B” cathodes:

- The “A” cathodes are subject to 150% current density for two periods while the “B” and “C” cathodes are harvested. The two periods are separated by about three hours and last approximately ten minutes.
- The “B” cathodes are subject to 150% current density for two periods while the “A” “C” cathodes are harvested. The periods are of about ten minutes with one at the start of nucleation period, and the second end the end of the deposition cycle.
- The “C” cathodes are only subject to 150% higher current density at the end of the growth cycle for two periods of ten minutes each with a three hour gap between them.

At least four operations have been investigated that have used this style of harvesting; although more are likely to be doing so.

Electro-refining Block Stripping

This method of stripping was a direct transfer from the ‘dead’ stripping used in electro-refineries where the section to be stripped is isolated from the DC current supply. However in electro-wining the harvesting is ‘live’. In this method (Figure 2c) a complete block of one third of the cathodes (Block “A”) is removed from the cell for harvesting; leaving a large space with no current flow. Once the stripped cathodes are replaced in the cell the second block of one third of the cathodes (Block “B”) is harvested; also leaving a large gap in the cell for concentrating current flow. Finally the last one third block of cathodes is harvested (Block “C”); again leaving a large gap in the tankhouse DC current flow.

The currently density and temporal pattern on the cathodes and anodes are ultra-extreme:

- The “A” Block and “C” Block cathodes next to the harvested “B” Block cathodes are subject to extreme current densities in the first few cathodes next to the harvested block. It is difficult to estimate the current but up to +250% nominal current density is expected in the nearby cathodes. The ultra-high current densities are imposed for periods of about ten minutes and with ten minutes between the episodes.
- The “B” Block cathodes next to the harvested “A” and “C” Block cathodes are also subject to extreme current densities as described above.
- The cathodes in each block remote from the harvested block (outside cell ends on blocks “A” and “C”; and inside block “B”) have only minor increases in their operating current density.
- The current flow to the majority of lead anodes is stopped in the blocks from which cathodes are removed.

Block Stripping of the “A” cathodes from a number of cells is shown in Figure 3. With at least three cells harvested (or ‘open’) the time of applied extreme poor current distribution will ensure that there are a lot of shorts and heavy growths at the block margins.

Figure 3 – Block stripping the “A” cathodes in three cells.

The electro-refining block stripping method has been implemented at one operation in Australia (Riles and Lancaster, 2000) that was then relocated to the Democratic Republic of Congo. The same stripping method was implemented without modification (G. Miller, personal communication, September 27, 2013). The same method was also employed in one operation in the USA.

EFFECTS OF HARVESTING ON CATHODE QUALITY

The effects of harvesting on cathode quality are primarily related to two fundamental aspects of the process of copper deposition: the time and limited current density required for consistent nucleation of crystal growth in the preferred orientation of parallel to the plate. Higher nucleation current densities for longer periods of time will result in more cathodes with the non-preferred growth direction, perpendicular to the cathode plate. Nucleation and growth in this orientation will lead to more dendrites and generation of growth shorts with lower current efficiencies. Once initiated in the non-preferred orientation, it is very difficult to change the growth orientation back to the preferred one; until the copper has been harvested. With the incorrect growth orientation the crystals are not packed tightly on the cathode which results in brittle copper that is difficult to strip and contains high levels of occluded electrolyte.

If high current densities are imposed on already properly nucleated and partially grown copper, then a change in crystal growth orientation can occur to grow dendrites. The operating current density at which this occurs has been increasing in recent years but is in the region of 550 - 650 A/m^2, dependant on the particular cell operation characteristics and the duration of high density operation. Longer periods lead to a higher proportion of cathodes with undesirable crystal growth orientation. Once the growth orientation has been changed to the non-preferred state, it difficult to change it back until the copper has been removed by harvesting.

Another aspect of high local current densities is the increased anode corrosion. This occurs from both the high applied current and the sudden changes in current density, including cycling anodes to zero current; that can cause the lead corrosion product to spall from the anode. It is not unusual to have both poor copper quality, from high current density effects, and to experience concurrent high product lead levels. By considering the absolute current density and the temporal pattern of high current density application; fundamental reasons are provided to explain the effects on copper quality and anode life.

'Every Third' Method

The 'every third' method has the lowest locally and average imposed increased current densities during harvesting. It also has the second longest time of two days between replacing a stripped cathode and subjecting it to a higher current density when stripping its immediate neighbour. The initial copper growth has the best opportunity to start in the preferred orientation during the first two days of average current density operation. For the short ten minute period when it is subject to 150% of average current density the copper is not subject to sufficient stress to force a change to the alternate crystal growth orientation. Operating typically at 320 A/m^2 the higher harvesting current density is limited to an average 480 A/m^2.

Aslin & Eriksson (2011) have tested the current distribution during harvesting. Figure 4 shows that during 'every third' harvesting of cell 69, there is little current distortion between cathodes, and current distribution remains uniform.

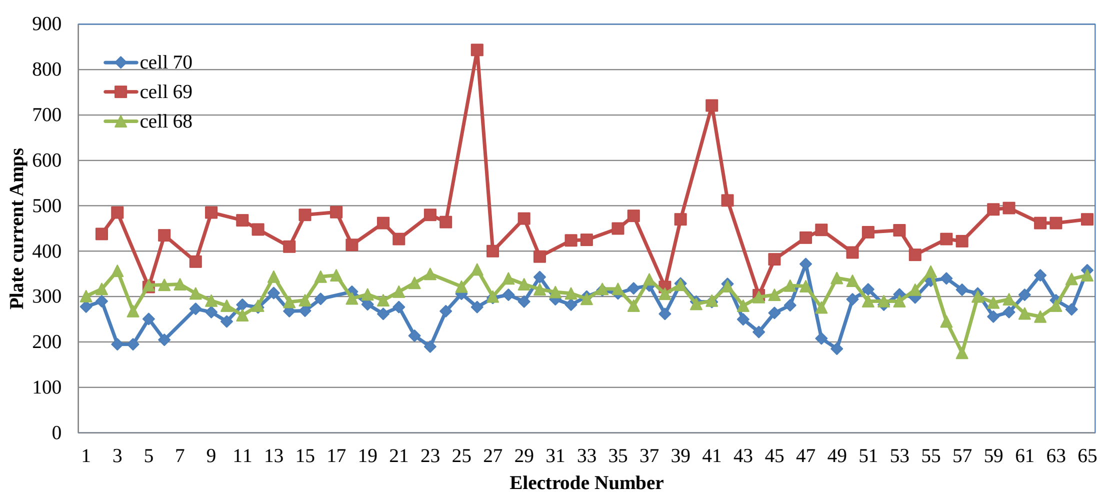

Figure 4 - 'Every third' stripping cathode current distribution for 3 consecutive cells

Figure 5 shows the effects on anode current distribution using the 'every third' method. Uniform current distribution is maintained across the cell for the remaining cathode plates (with the exception of short circuits in cathodes 26 and 41). Anode current density is more erratic as two out of three anodes have one companion cathode missing and therefore draw less current. Importantly however all the anodes stay active (albeit at lower current) which helps to avoid oxidation / spalling and prolongs anode life.

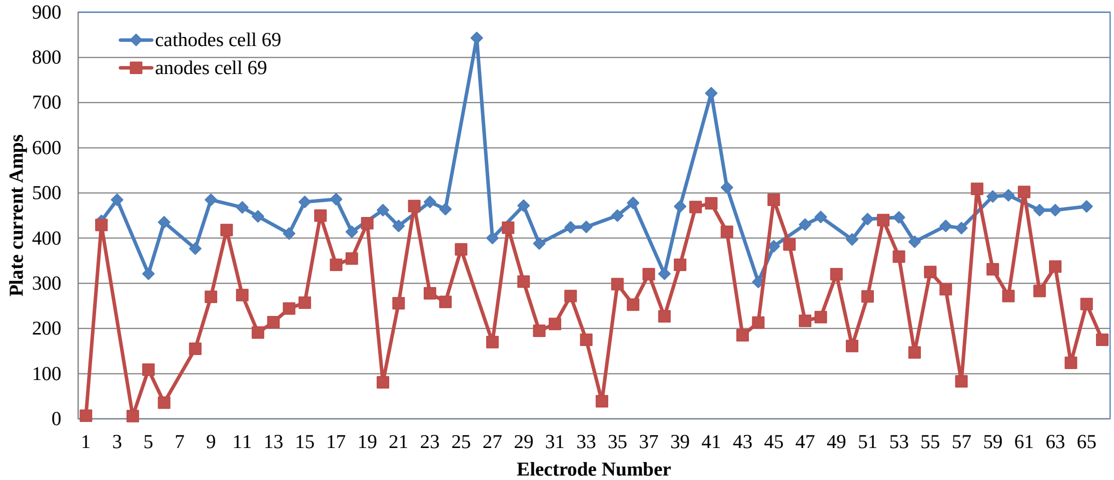

Figure 5 - 'Every Third' stripping current distribution for anodes and cathodes

With the cathodes having the preferred crystal orientation, the copper is stiff and relatively easy to strip with simple flexing of the mother plate. The lack of high current density driving force to change the crystal growth orientation means that growth shorts are minimised and current efficiency is high. The hard deposits are low in intra-crystal electrolyte so that sulphur levels are low. The low level of shorts minimises any lead contamination from direct cathode- anode contact.

The anodes are also only subject to short duration (ten minutes) higher current density events with long intervals of two days between them. As a result the electrical stresses are spread out over time, giving the brittle anode lead dioxide corrosion product a chance to recover coherence. With less lead discharged from the anode, there is generally lower lead levels in the product cathode. A further benefit from the benign conditions on the anodes is that their operating lifetimes are extended.

'Every Second' Method

The 'Every Second' method harvests every second cathode from a cell. This means that the imposed current density on the other growing cathodes will be 200% of the nominal average current density. When operating at nominally 320 A/m^2 the resulting average density is 640 A/m^2, with several electrodes at higher levels depending on the current distribution within the cell. This is the highest universally imposed current density of any harvesting method. As a result the product quality can be variable with changes in the growth morphology from the period of 200% of nominal current density. The current density imposed may be beyond the limiting current density for commercial copper plating which would have a significant impact on crystal structure. The growth upset time is actually higher than the nominal harvesting time as the high current density through the remaining cathodes is propagated throughout the tankhouse. As shown by Blackett & Nicol (2010) more than five cells can be affected by the mal-distribution, for the cumulative period of the harvest, usually several hours per day.

Evidence of this is provided by examination of the microstructure in Figure 6 of a typical deposit grown under these conditions (Aslin & Eriksson, 2011).

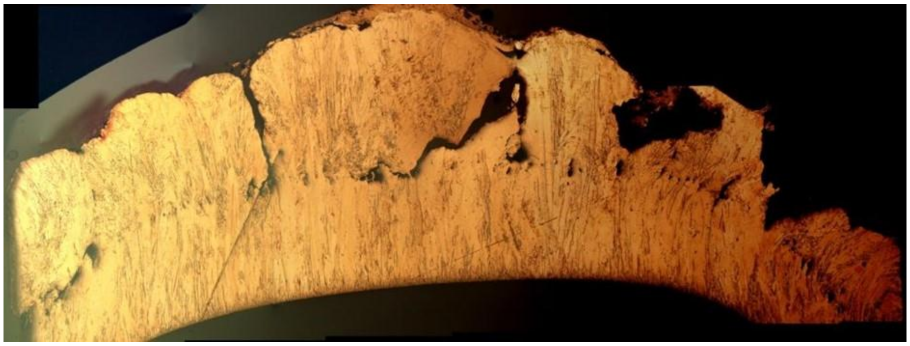

Figure 6 - Microstructure of ‘Every Second’ style harvested copper

Comments on the microstructure are:

- Band of porosity mid-way through the growth cycle - caused by ultra-high current density (640A/m^2) during harvesting of the companion cathodes.
- Growth changes from close-packed elongated grains (good structure) prior to the event, to dendritic growth after the event.
- The outer porous structure of the deposit will occlude electrolyte generating a high concentration of sulphur. As an example the inclusion of as little as 0.25% v/v electrolyte (with 35 g/L Cu and 180 g/l H_2SO_4) within the interstitial grain structure, the product sulphur level will typically be +20 ppm.

As a result of the change in growth morphology there is an increase in short generation; leading in turn to low current efficiency. The presence of shorts will increase the lead content of the cathode from direct contact. Anode corrosion rates will be high with significant discharge of scale from the high current density shock during harvesting.

The high currents and current density on the cathodes also cause thermal heating effects on these electrodes. Warping of the stainless steel blade and sagging of the header bar can result (Weston & Web 2003). These dimensional changes can increase the number of poor alignment proximity shorts; with consequent lower current efficiency and high lead in the product copper.

Operations using this stripping method have had severe and long term issues with product quality and market acceptance (Readett & Mark; P. Hutchinson, personal communication, October 10th 2013).

Starter Sheet Style

The major issue with the starter sheet style of harvesting is the very short period of time that the “A” and B” cathodes have to start nucleation before being subjected to 150% of current density. The “A” cathodes are stressed twice within a small 20 minute window of being replaced; and the B cathodes on one occasion; but again after only a few minutes of being put back into service. As expected from this current / time interaction, product quality is generally poor with occasional good results being obtained. Observation of a typical set of buttons from three cathodes (diagonal punched in a nine-hole pattern) in Figure 7.

Figure 7 - Sample buttons from starter sheet style harvested cathodes

The individual buttons have been labelled as:

P	poor quality	from the "A" cathodes
G	good quality	from the "C" cathodes
S	suspect of poor quality	from the "B" cathodes

The visual indicator of good quality is a smooth bright exterior with no signs of nodulation or surface cracking. This shows that the crystal growth pattern is across the mother plate – forcing the crystal edges to grow together and force out any interstitial electrolyte. As a result the sulphur in this sample will be low.

With the different deposit growth morphologies evident in the product from this harvesting pattern, the stripping characteristics are also profoundly different.

- The "A" cathodes are brittle and difficult to strip coming off the mother plates in pieces and chunks. Many do not strip and need to be rejected for hand removal and plate remediation.
- The "B" cathodes are not as brittle but are still difficult to strip in a machine; and require significant manual intervention to remove the flexible copper from the mother plate. Rejection of poorly stripped plates is still an issue.
- The "C" cathodes are easy to strip and show few rejects for poor copper removal.

The poor crystal structure of the deposit is a prime diver for the development of dendritic growth and development of shorts. Typically tankhouses using this harvesting method have difficulty in maintaining current efficiency above 75% (D. Jacobs, personal communication, September 16, 2013). With the significant number of shorts, the lead content in cathode from the short contact on the anode is generally elevated with + 5 ppm common in run of plant sample tests.

The anodes have been subject to short duration 150% current density increases but at short time intervals. As a result they tend to have higher corrosion rates from flaking of the lead dioxide layer. This is particularly true of the anodes around the "A" cathodes where they have two such incidents within thirty minutes. Overall this can result in elevated lead levels in the entire product from the floating flakes exfoliated from the "A" anodes.

A number of plants using this style of harvesting have been changed to the "one in three' style. Immediate positive changes have been seen with the product morphology becoming much harder and easier to strip (R. Silwamba, Personal communication, July, 2008). The sulphur levels dropped immediately. The lead levels have taken longer to return to specification as the accumulated lead scale inventory needed to be removed from the cells.

Modified Starter Sheet Style

The modified starter sheet style of harvesting has longer times between the return of the high current density to the recently replaced stripped cathodes. As a result the changes in growth morphology are not as marked as with the true starter sheet method. Even so the same types of results are evident, but to a lesser degree. Shorts are common, elevated lead is common and current efficiency is still low, albeit at a slightly higher level of around 80% (S. Williams, personal communication, September 8, 2013).

One recently commissioned operation began harvesting using this method in a number of separate electrowinning plants. Low current efficiencies prompted a trial of the full 'one in three' harvesting method. The results were positive with an immediate reduction in the number of shorts and with an increase in current efficiency to 85%. One of the attributes of the 'one in three' harvesting is that every third cathode has a two day growth difference with its neighbours. There was an immediate reduction in the number of shorts per cell simply due to the lack of growth on two thirds of the cathodes. Short detection and removal was easier and quicker; and the consequent upset in current distribution reduced. .

Electro-Refining Block Stripping

The outcomes from this method of harvesting can be quite diabolical. The ultra-high current density on the few cathodes near the end of the block being harvested is so high that dendrite growth and shorts are almost always apparent in every cell. These are most prevalent in two rows cathodes down the entire cell house. The rows are at the block A-B and block B-C interfaces, where the ultra-extreme current density is imposed. Since the stripping is carried out down the cell aisle the ultra-high imposed current density is propagated to all the other cells; increasing the time and number of incidents that each is subject to the high currents.

When operating at nominal capacity the cathode weights at these interfaces were up to 60 kg per side while those from the outer ends of the cells were 40 kg per side (T. Lancaster, personal communication, 2002). Correspondingly there were a large number of shorts and low current efficiency (Riles & Lancaster, 2000). However when operating at low average current density of less than 200 A/m^2 the product quality is better as the peak current density during harvesting is limited. Shorts are reduced, deposit morphology is acceptable for stripping and a majority of the product meets Grade A specification.

Figure 8 shows the effects on measured cathode current distribution for 'block' harvesting methods (N. Aslin, personal communication, November 4, 2013). Block stripping produces distortions in current distribution for both the cell being harvested (69) and its immediate neighbours. This effect has been shown by Blackett and Nicol (2010) to propagate several cells from the one being harvested. Plates close to the removed 'A' block cathodes are subject to higher than normal current density and frequently experience short circuits (e.g. plate No.40). In the neighbouring cells there is a clear reduction in current density of 30% to 40% for the plates adjacent to the A-block and a corresponding increase in the remainder of the cell.

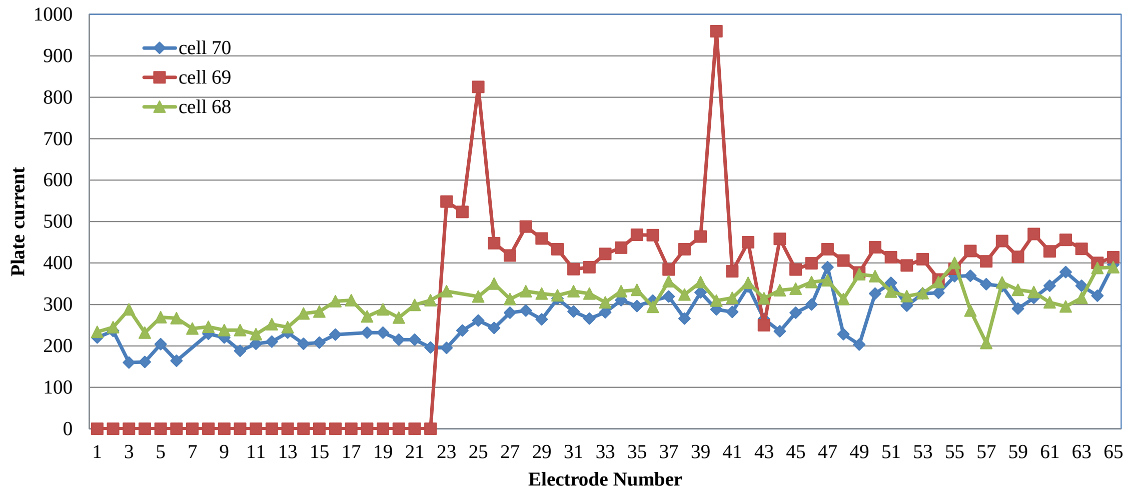

Fig 8 - Block stripping cathode current distribution for 3 consecutive cells

Figure 9 shows the effects on anode current distribution using the "block" harvesting method. During block stripping most of the anodes in Block A become inactive as expected, and are therefore subjected to corrosion and thermal stresses described previously. The small current flow occurring in some of the anodes is the result of 'stray' current flow to the next closest cathodes.

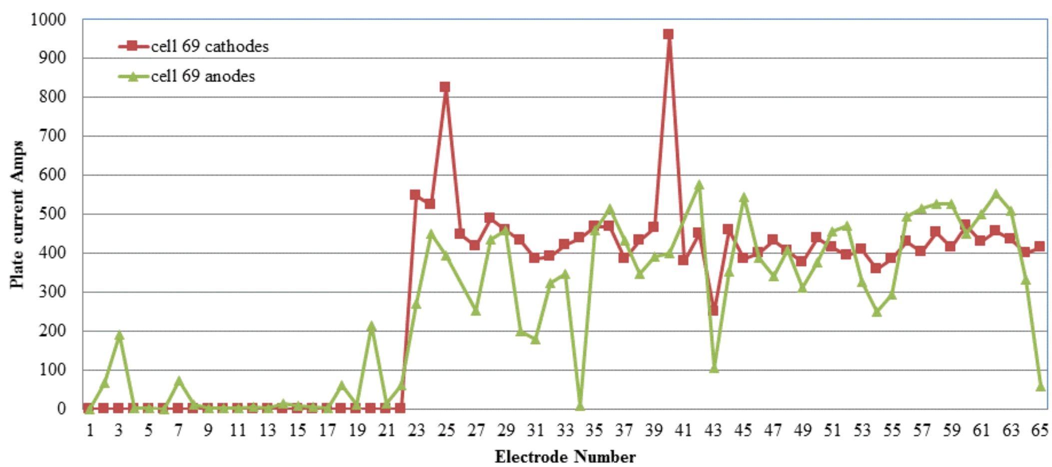

Fig 9 - Block stripping current distribution for anodes and cathodes

Other impacts on the EW are also severe with the localised high currents at the ends of the blocks that remain in the cells.

- The inter-cell copper bus bar and electrode insulators often melt.
- The capping boards and electrode chairs are damaged by heat and fire.
- A significant number of electrode hanger bars melt or weld themselves to the inter-cell bus bar.
- Thermal stresses from heating of the electrodes can cause significant warping and twisting with consequent proximity shorts, low current efficiency and shorten electrode life.
- Local acid mist evolution can become extreme with operating conditions unfit for personnel without breathing apparatus.
- Increased local corrosion of the electrode header bars from the increased acid mist and oxygen evolution.

The relocated plant in the DRC has changed the harvesting from this style to the one-in-three style. In order to achieve the outcomes the stripping conveyors were extended, the conveyor drives upgraded and a new cathode lifting bale procured. A change over plan was developed so that no cathode had more than eight days' growth, and less than four days. The change-over was successful with immediate benefits in the elimination of the effects of the ultra-high local current densities. Product quality has improved with the lessening of shorts. Stripping effectiveness has improved with the harder more dense deposits. Current efficiency has increased from 75% to 85% without changing any other parameters (A. Modi, personal communication, October 10, 2013).

BEST PRACTICE OPERATION

In most operating plants best practice operation is not generally carried out fully. Specific operation conditions may preclude some of the practices from being implemented. However it is appropriate that in a discussion of harvesting methods that the best practice methods should be included to allow the industry to at least be aware of them as potential methods to reduce the costs of operation.

The most important one is to minimise the amount of time that plates are exposed to high current density, particularly with half-cell ('Every Second') harvesting. In this way the potential effect on the crystal morphology can be minimised. In order to ensure that this is the case a supply of stripped cathodes is needed in or at the stripping machine to allow an early return of cathode blanks to the harvested cell. Methods of implementing this arrangement can include:

- Plates from the first cell are taken to the cathode stripping machine (CSM) at the start of the day's stripping
- The crane immediately returns with blank plates from storage
- Storage is either
    - The CSM stripped cathode conveyor (or rack) or
    - A rack(s) of spare plates kept on the ground floor to be used for backfilling cells in the event of a CSM breakdown or extended stoppage.
- At the end of the day's stripping excess plates are returned from the CSM to the storage racks.

This procedure should limit high current density exposure to 10 to 20 minutes; thereby improving cathode quality by reducing nodulation with the shorter time of exposure.

One 'Every Second' type operation followed a recommendation to back-fill cells straight away during harvesting (Aslin & Eriksson, 2011). This reduced the exposure time to very high current density from one to two hours to less than 20 minutes. An improvement in cathode quality resulted from this change as well as other changes made at the same time.

The second most important is to select a harvesting method that has the lowest increased current density on *all* growing deposits when their neighbours are being harvested. The harvesting methods in *increasing order* of harvesting current density are:

- 'Every third', modified starter sheet, starter sheet – all equal (150%)
- 'Every Second' (200%)
- Block (300% on nearby cathodes)

The third most important is to select the harvesting method that has the longest time between the replacement of the new cathodes and their being subject to higher current density operation when their neighbours are being harvested. The harvesting methods with the longest to shortest times are:

- 'Every Second' (three days)
- 'Every third' (two to three days)
- Modified starter sheet (four to six hours)
- Block and starter sheet (ten to twenty minutes)

The effect of changing from one harvesting method to another can be significant. When changing from Starter Sheet to 'every third' harvesting, an immediate improvement in product quality was obtained (R. Silwamba, personal communication, July, 2008; D. Jacobs, personal communication, September 16, 2013). When changing from Modified Starter Sheet to 'Every third' there is an increase in product quality and a decrease in shorts (S. Williams, personal communication, September 8, 2013). Similarly changing from a Block harvest to an 'every third' harvest an immediate product quality improvement was evident as well as significantly reduced damage to anodes, cathodes and cell top furniture and bus bars (A. Modi, personal communication, October 9, 2013).

Considering the practical effects of following the combined best practices, the consistent and best quality copper is produced with short exposure time, low increased harvesting current density and with long periods between impositions of harvesting current densities. The ranking of harvest methods based on commercially achieved product quality is:

- 'Every third',
- Modified starter sheet
- 'Every Second'
- Starter Sheet
- Block

CONCLUSIONS

There is an effect on product quality, current efficiency and anode life from the harvesting method that is used for stainless steel cathodes. The effect is reduced for those methods that have lowest current density during harvesting, on remaining cathodes when combined with the shortest time of high current density and long intervals between episodes of high current density. Some of the harvesting methods exceed the critical nucleation current density (on some of the cathodes) with consequent very poor product quality.

Fundamentally and practically, the 'every third' method of harvesting (with extraction of every third cathode every two or three days) produces the most consistent high quality cathode copper. Best practice is to minimise the time that growing cathodes are subject to the harvest current density by ensuring a ready supply of stripped cathodes to replace into the harvested cell. The majority industry acceptance of the 'every third' harvesting method, as recommended by the XT's ISAKIDD tankhouse group, is due to the more consistent and higher quality product that this method produces.

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