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Towards On-line Monitoring of Alumina Properties at a Pot Level

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Abstract

Aluminum reduction cells typically use about 1.9 kg of alumina in order to produce 1 kg of aluminum. Hence, for modern reduction cells operating in the 350 to 400 kA range, 5000 to 6000 kg of alumina is fed to reduction cells on a daily basis. However, no information is available in an on-line fashion about the alumina properties fed to the pot. Alumina feeding control systems assume that alumina properties are constant for all pots within a potroom and also over time. Therefore, these control systems aim at controlling alumina concentration dissolved in the bath without accounting for the time varying effects of alumina properties and/or pot condition on alumina dissolution. Based on sampling campaigns, this paper presents evidences of time varying alumina properties impacting its dissolution rate and also proposes a novel approach in order to measure on-line, at the pot, parameters that are related to alumina dissolution.

Introduction

Aluminum metal is produced through the electrolytic decomposition of alumina dissolved in a molten bath of fluoride salts. The electrolytic process takes place in hundreds to thousands of reduction cells enclosed in a smelter. Even if some operations such as metal taping, anode setting and beam rising are done discretely, the cells operate continuously for 4 to 10 years and alumina needs to be continuously feed during all those years. For the first 60 to 70 years of this industry, alumina was manually added to each pot in large quantities (i.e. up to hundreds of kilograms) at a low frequency (i.e. many hours). This operation was labor intensive and was also detrimental to stable pot operation as the pot was operating at really alumina concentration, close to alumina saturation, shortly after the alumina was dumped in the pot, all the way down to low concentration. This implied that some alumina sank down to the bottom, following the drastic addition, and was later operated towards anode effects as it consumes the alumina. This operating mode was detrimental to thermal balance, current efficiency, energy consumption and environmental emissions.

In the early 1960, Alcoa developed the point feeder, a device used to punch a hole in the crust covering the molten bath and to deliver a shot of alumina [1]. These devices are mounted inside the pot superstructure with one or many alumina storage bins. As a result it was no longer necessary for the operators to manually deliver alumina to the pots, but also greatly improve process stability as it is now possible to feed smaller shots of alumina (i.e. 1 to 2 kg) at a much faster frequency (i.e. in the order of minutes). Therefore, the pot does not sustain high variations in alumina concentration which greatly help improving performances. Modern pot technologies are now all equipped with point feeders and many Søderberg plants have been retrofitted with point feeders [2, 3].

Later, in the 1970's, alumina feed control, still used today in the industry, was introduced [1, 4]. This is done by tracking the change in the pot resistance over time as the alumina is depleted from the bath.

Figure 1 presents variation of cell resistance as a function of alumina concentration and Figure 2 presents the time derivative of cell resistance as a function of alumina concentration for some pot technology. By switching from overfeed to underfeed, it is possible to operate the pot on the right hand or on the left hand side, respectively, of the curves depicted in Figures 1 and 2. By switching off the feed, the control system monitors the time derivative of the resistance and determines if the pot is on the rich or lean side of the curve depicted on Figure 1.

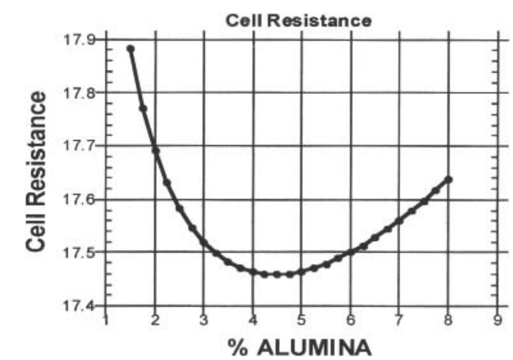

Figure 1: Relation between pot resistance and alumina concentration.

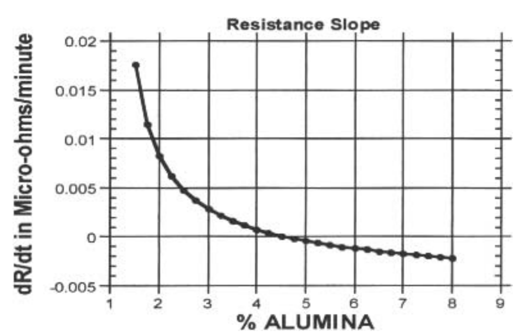

Figure 2: Time derivative of the cell resistance as a function of alumina concentration.

Doing so, it is possible to operate the pot closer to the optimal concentration therefore maximizing pot performance.

Since then, many improvements have been made on the feeding operation and on controlling the alumina concentration of the molten bath. However, the industry is still using the underfeed/overfeed without knowing too much nor taking into account variations of alumina properties and its impact on alumina dissolution. At best, process engineers may change different parameters to optimize the feeding on a weekly or daily potline basis, based on scarce alumina sampling, rule of thumbs and approximate estimations of time delays in the alumina transport system within the smelter. For *lucky* smelters directly connected to an alumina refinery, alumina properties may be available on a daily basis which may facilitate this manual optimization. However, this is not the case for most smelters importing alumina from one or many suppliers.

This paper aims at developing an on-line monitoring solution of alumina properties linked to alumina dissolution rate. First, this paper presents results obtained from alumina dissolution studies in a lab cell. Secondly, a statistical investigation, at a smelter level, on factors correlated with alumina dissolution rate is presented. The variability encountered in this study motivates the development of a sensor to follow the variations of alumina properties on a pot level, which enable to monitor properties correlated with alumina dissolution. This is presented in the third section. Finally, monitoring results obtained using the sensor during plant trials are presented and possible implications for pot control are presented.

Alumina Dissolution

In order to operate a pot close to its maximum productivity it is important to achieve and promote a rapid dissolution of alumina particles following an alumina shot. That is obtaining a high dissolution rate.

Many factors are believed to have an impact on alumina dissolution, or more importantly on the rate at which it dissolves. For instance, these could mainly be divided in two categories; pot operating parameters and factors related to alumina properties. A good study of these parameters is presented in the literature [5, 6]. Of interest in this study are the alumina properties related to alumina dissolution rate.

Many studies have been performed in order to determine which alumina properties are the most important for alumina dissolution. It is known, for example, that alpha phase alumina dissolves more slowly compared to other phases [7]. The impact of the amount of fines, moisture on ignition, gamma and alpha content and particle size distribution on alumina dissolution were also studied [5, 8]. Similar studies were carried out at Alcoa Technical Center [9, 10]. Amongst all alumina parameters that were varied during this study, a good correlation was found between alumina flowability and dissolution rate. Faster flowing alumina typically seems to disperse better over the bath and therefore promotes faster dissolution. Alumina flowability or its readiness to spread over molten bath surface plays a critical role in the forming of floats/rafts/agglomerates/crust. Thin rafts/floats penetrated with more and deeper bath components are preferred since they are fast disintegrating and fast disappearing ones due to the direct eutectic melting before α-phase transformation, which in turn affects overall dissolution rate/process. Figure 3 presents the maximum dissolution rate as a function of alumina flow funnel time (flowability) [10]. This plot also shows a linear and a quadratic relationship between the maximum dissolution rate and the flowability. The linear fit explains 61% of the variance of the maximum dissolution rate and has a root mean square prediction error of 0.019. On the other hand, the quadratic fit explains 64% of the variance of the maximum dissolution rate and a has root mean square prediction error of 0.02. Both models lead to similar results. Even though it cannot be concluded if there is a linear or a quadratic relationship, one can still appreciate the lower maximum dissolution rate as the alumina flowability increases.

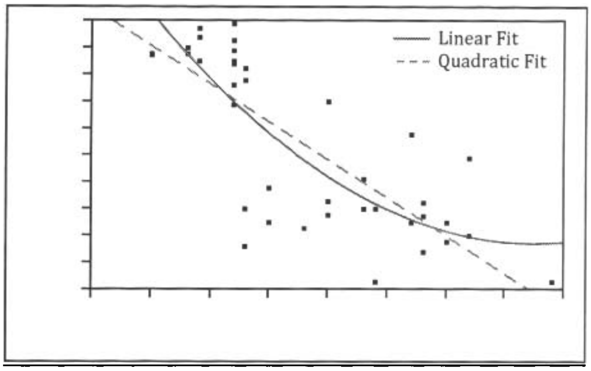

Figure 3: Maximum dissolution rate as a function of alumina flowability.

Based on these results, a sampling campaign was carried out at one of the Alcoa smelter in order to study variations of alumina flowability and hence dissolution rate on different basis.

Variation of Alumina Properties

Alumina was sample at a pot level from five pots, at the beginning of the sampling campaign, and later from three of these pots. A simple ladle is used to grab the alumina shot as it exits the point feeder. From there, samples were weighted, so that the shot weight is known, and were cured according to an in-house procedure so that the electrostatic charges would dissipate before the flowability analysis. Samples are weighted to 250 g (+/- 1 g) and poured in an Alcoa designed brass funnel equipped with a 6 mm orifice (Figure 4) [11]. More than 3500 samples have been gathered over more than 3.5 years on almost a daily basis.

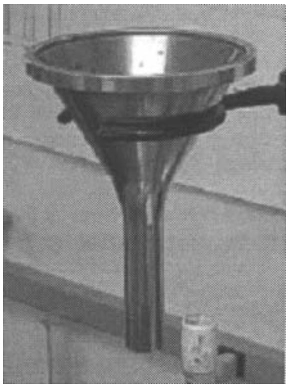

Figure 4: Alcoa alumina flowability test equipment.

This equipment was used to analyze the samples in order to determine the variations in alumina flowability on different basis.

Over Pots

Based on this particular smelter experience, it was noted that there is some important segregation along the length of the potroom. This creates significant differences in flowability on a pot basis. Hence, the five pots selected for the sampling campaign were distributed along one of the lines. Table 1 presents average flow funnel time for the 250 g samples on a pot basis. Each letter of the third column of this table, and also for all tables below, indicates levels that are significantly statistically different at a 95% confidence level using Tukey-Kramer test for mean differences [12]. This table shows that each pot receives alumina characterized by a significantly different flowability. Independently of the alumina processed in the smelter, these differences always exist over time.

Table 1: Average alumina flowability on a pot basis.

Pot	Flow Funnel Time (seconds)	Class (95% Confidence)
A001	109	A
A033	152	B
A066	119	C
A100	87	D
A132	59	E

At many occasions, samples were gathered from the four feeders mounted on each pot. On each occasion, there was no statistical difference in alumina flowability, indicating no signs of segregation on a feeder basis within a single pot. This is mainly due to the hyper dense system delivering the alumina from the distribution system to the four alumina bins inside the pot superstructure. The bins are always full and hence storing and delivering alumina with similar properties.

Over Supplier

However, when the smelter changes alumina supplier, there is sometimes a step change in the average flowability for the whole potline. This step change could be drastic or may take some time depending on silos inventory before the different alumina was received at the smelter. During the sampling period, the smelter was supplied with alumina coming from five different refineries. By sorting flow funnel times according to suppliers, it is demonstrated that there is some statistically different differences in alumina flowability between alumina suppliers.

Table 2: Average alumina flowability on an alumina supplier basis.

Alumina Supplier	Flow Funnel Time (seconds)	Class (95% Confidence)
1	117	A
2	95	C
3	103	C
4	99	C
5	110	B

Impact From Upstream Processes

For different reasons, the maintenance crew needs to perform some maintenance operations on the alumina distribution system on Mondays. This affects alumina daily tanks level as they are not filled during the maintenance. As the daily tanks level shrink, the pots are fed with finer alumina particles, resulting in statistically slower flowability on Tuesdays and slower, but not significantly, on Wednesdays. Interestingly, the reader should note that the average flow funnel goes down until the next Tuesday, indicating that less fine material is fed as the time since the last maintenance operation increases.

Table 3: Average alumina flow funnel time on a day of the week basis.

Day of the Week	Flow Funnel Time (seconds)	Class
Sunday	102	B
Monday	102	B
Tuesday	115	A
Wednesday	108	A - B
Thursday	105	B
Friday	104	B
Saturday	103	B

Over Time

Overall, when looking at the whole picture, alumina flowability could greatly vary over time for this smelter. Figure 5 presents a plot of the alumina flowability for one pot, on a daily basis, for the sampling period. For example, it is possible to see a step in alumina flowability following a supplier change, depicted by the red dotted line, from supplier 3 to 5. Also, more frequent high amplitude fluctuations could be observed over the complete period. A spectral density analysis of the flowability, presented in Figure 6, indicates that the dominant frequencies are in the 0.05 to 0.1 days^{-1} range (10 to 20 days period) while some strong frequencies are also present in the 0.15 to 0.3 days^{-1} (4 to 7 days period). The 4 to 7 days period is characteristic of the maintenance operations on the alumina distribution system, while the 10 to 20 days period is characteristic of the switch between alumina suppliers.

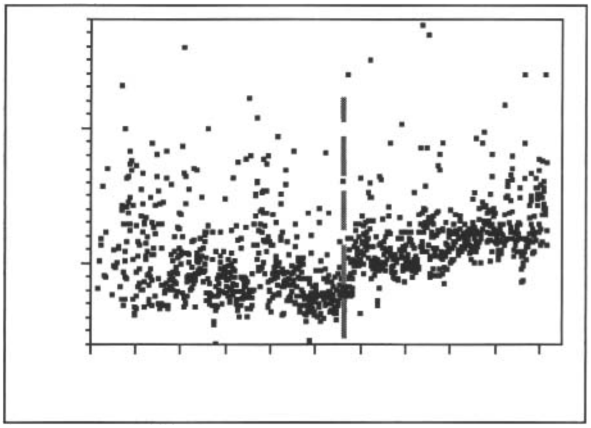

Figure 5: Alumina flowability for pot A001 over the whole sampling period.

However, some faster variations of alumina flowability are also noticeable at a faster sampling frequency. On three different pots, alumina was sampled from the four alumina feeders at a 15 minute time interval for almost 8 hours. Figure 7 presents the alumina flowability from feeder 1 of pot B030, sampled on Tuesday November 16, 2010. The average flow time for 250 grams of alumina is 188 +/- 7 seconds. However, a maximum flow time of 237 seconds and a minimum of 155 were measured during the 6.5 hours sampling period. This indicates that, even within a few hours, there are some fast variations in alumina quality that cannot be accounted for by the alumina feeding control system.

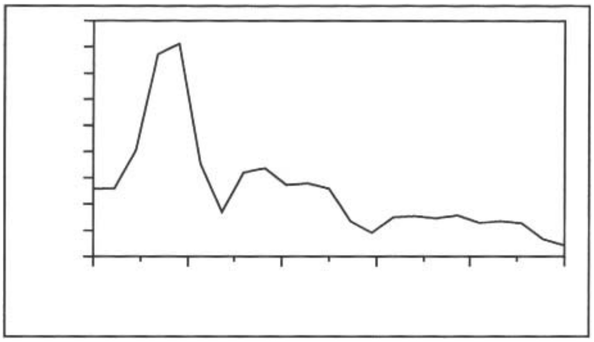

Figure 6: Spectral density of alumina flowability when collected on a daily basis from pot A001.

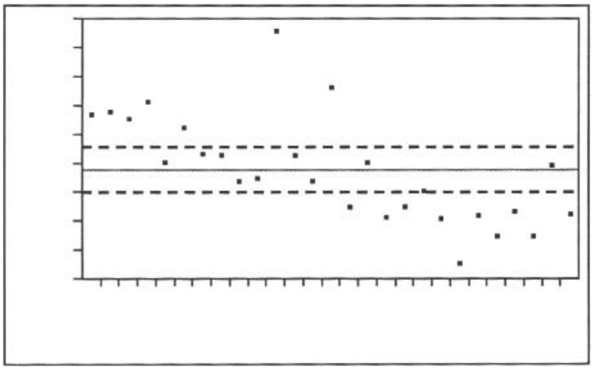

Figure 7: Alumina flowability for pot B030 over an 8 hours period.

Based on these results, it is clear that a smelter sustains variations of alumina quality, at different frequencies and possibly on a pot basis. However, these variations are not observed or monitored and it is hence impossible to react in a promptly fashion to optimize alumina feeding control parameters. Based on this study, an effort was made at developing a sensor for on-line monitoring of alumina flowability as it varies over time and his correlated to alumina dissolution rate.

Sensor Development

Different sensors were investigated and tried. However, the harsh potroom environment is problematic when time comes to put some instrumentation on or inside a pot. High temperatures, dust, magnetic fields and fluoride gases on top of electrical insulations turn into barriers limiting the sensor choice

The AP-30 type of pots are equipped with four separate crust breakers and alumina feeder devices. The alumina feeder is at 25 cm from the crust breaker. Hence, a feeder pipe is used to deliver the alumina from the feeder to the feeding hole. The feeder pipe and the crust breaker are illustrated in Figure 8.

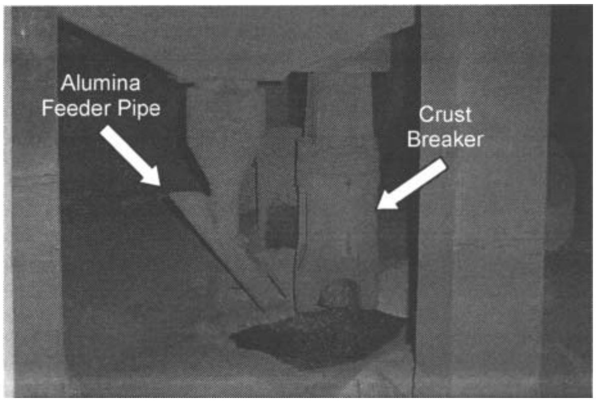

Figure 8: Arrangement of the alumina feeder, feeder pipe and crust breaker for an AP-30 type of pot.

The alumina feeder pipes used at this smelter create en effect that is similar to the analytical funnel used to measure alumina flowability (i.e. Figures 4 and 8). The alumina is dropped in a big recipient with a funnel type outlet underneath it. However, in order to improve the sensibility of the sensor, a flow restricting device was added to the actual feeder pipe. The restriction increases the time it takes for the alumina to flow from the delivery point to the bottom part of the feeder pipe. This has two effects. First, it increases the sensor sensitivity as it stretches the flow time between good and bad flowing alumina. Secondly, it increases slightly the times it takes to deliver the alumina. This may improve how the alumina is dispersed on top of the molten bath and hence improve the dissolution process.

From a laboratory test based on different alumina samples, a correlation coefficient of 0.93 was found between the analytical flow funnel time and the time it takes for an alumina shot to flow through the feeder pipe using the flow restriction. Hence, it is possible to measure the alumina flowability at a pot level using the alumina feeder pipe. This greatly simplifies the problem as no moving parts such as sampling devices have to be installed on the pots. The only equipment that needs to be added is a sensor.

Following different tests, it was found that a type-K thermocouple is a good sensor for alumina flowability estimation. The feeder pipe is typically hot, over 150°C, and sometimes extremely hot when flames are directly in contact with the pipe (over 500°C). On the other hand, the alumina is at 60-65°C. Hence, it is possible to detect the flow of alumina within the feeder pipe by tracking the thermocouple temperature. The signal goes into a custom signal processing routine and is converted into a flowability index.

Therefore, a simple cost effective solution was found for an AP-30 type of alumina feeder. Figure 9 presents a picture of the instrumented feeder pipe during prototype development.

Pot Trial

Following successful laboratory trials of the instrumented feeder pipe, a plant trial was first executed on three different pots, to demonstrate the concept and ensure that the sensor is sensitive enough to measure alumina flowability within the operating range. Instrumented feeder pipes prototype were installed on each four feeders and connected to a data logger in order to record the sensors signal for later analysis. During these tests, alumina samples were grabbed every 15 minutes, weighted, cured and analyzed using the analytical funnel. Analytical flow funnel test results for pot B030, feeder 1 are presented in Figure 7.

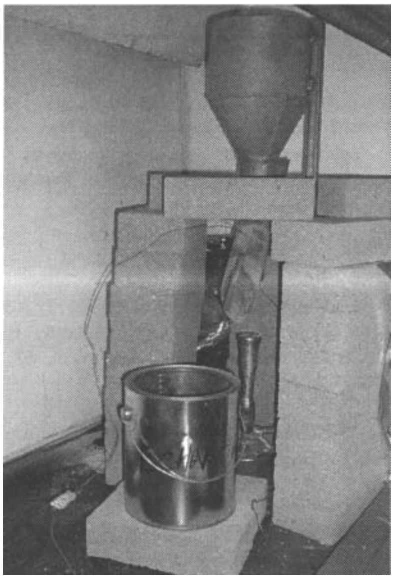

Figure 9: Instrumented feeder pipe prototype during lab trials.

Figure10 presents predicted alumina flowability using the sensor as a function of the analytical flowability for pot B030. Based on this 3 pots trial, the sensor is able to explain 85% of the flow funnel time variance and has a prediction error (RMSE) of 5 seconds, which is deemed to be precise enough for control purposes (~ 6% of the range).

Pilot Plant Deployment

Following the successful pot trial, a team was commissioned in order to develop a prototype solution in order to implement the sensor on a group of 10 pots. A solution was hence proposed, designed and installed on 10 pots distributed along the potline in order to monitor variations of alumina flowability in a real time fashion.

At first, some of the hardware parts were installed on a pot while the team was finalizing the solution. The objective was to determine if the hardware is robust enough to last inside a reduction cell. The hardware was installed on a pot for 57 days. During that period of time, more than 75 000 kg of flowing alumina of was in contact with the sensor. Unfortunately, the feeder pipe and the sensor were knocked-off by a PTM scoop during an anode setting operation. During this period of time, weekly routine checks demonstrated that the sensor worked properly.

In September 2011, the 10 sensors were installed on 10 different pots. The sensors send signals directly into the plant historian where they could easily be accessed. Figure 11 presents a chart of the sensor signal amplitude for a 7 minute period. During this time the feeder was delivering alumina every 60 seconds. It is clearly shown that the signal response drops drastically after an alumina shot and raises back, slowly towards its original level.

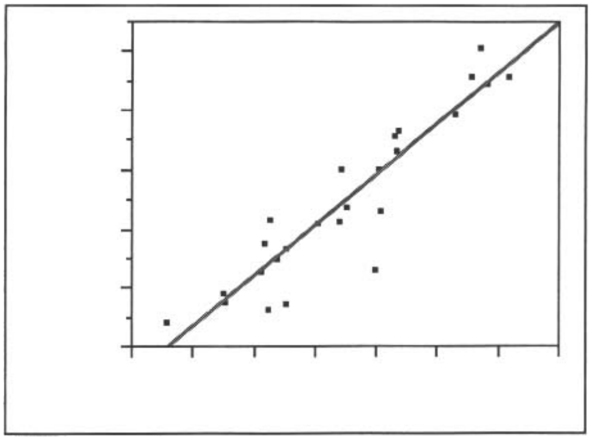

Figure 10: Predicted alumina flowability using the sensor as a function of analytical flowability measurement.

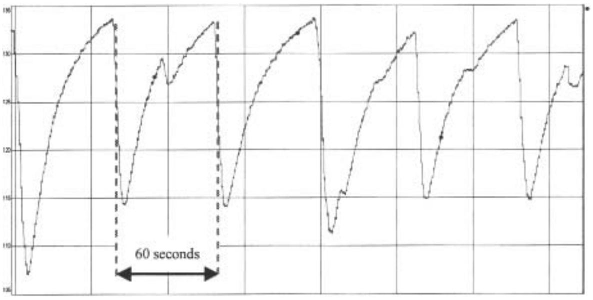

Figure 11: Screen shot from pot B003 instrumented feeder prototype.

At the time this paper was written, the code to convert back the signal into a flowability indicator, developed during the laboratory and pots trials was being coded into the plant historian. This will enable to predict alumina flowability for each shots.

Implications for Pot Control

The information on alumina flowability obtained from the sensors will be used to optimize alumina feed control. As this information will be available on a pot basis, for every alumina shots, different statistics can be computed in order to quantify the alumina in a dissolution rate basis. Real time optimization of alumina feeding parameters is now possible using this metric.

However, the advantage goes beyond optimization of feed control. From an alumina feeder working properly, it is expected that the sensor should detect a flow of alumina within a few seconds after the feeder received an order from the pot PLC. If the feeder does not detect a flow, an alarm is sent to the control room and an operator is required to attend the faulty feeder. This is advantageous as mechanical feeder failures are a high cause of anode effects. These faulty feeders are currently detected after an anode effect, when an operator performs an investigation. Hence, this new technology enables reduction of anode effect as mechanical failures related anode effects could be prevented..

Figure 12 presents a graph of the sensor signal over time for a faulty sensor. Just before the failure, the feeder was delivering alumina every 56 seconds. However, it suddenly stopped to deliver alumina and the signal started to drift. An alarm could be programmed to first turn-off the feeder and compensate the feed with the remaining three feeders and secondly to require an operator to attend the pot and fix the problem.

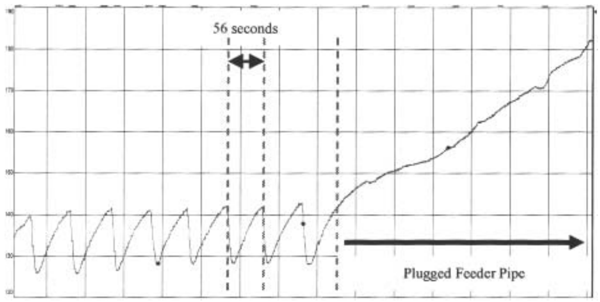

Figure 12: Screen shot from pot B118 instrumented feeder prototype.

Improvement of Alumina Dissolution

A plant trial is also underway to improve the alumina dissolution process. A group of 10 pots were equipped with restricted flow feeder pipes. The objective of this test is to determine if a slower delivery time for the alumina shot would improve its dissolution. The 10 pots have been using these modified feeder pipes for more than 150 days. During this period, anode effect frequencies were compared with a reference group of pots that are next to the test group, to account for the alumina segregation phenomena. A 4% reduction of anode effect frequency, statistically significant at a 75% level, has been noted on the test pots. The reader should note here that a high variance is typically associated with statistical analysis of anode effect frequency on a small group of pots. Based on these results, the test group will be increased to 33 pots and a more detailed analysis will be performed. On top of anode effect reduction, some benefits are expected on pot stability and performances.

Conclusion

In this paper, it was demonstrated that reduction cells from a single potline do not all receive similar alumina, from a dissolution rate stand-point. The alumina flowability, which is a good indicator of the dissolution rate, varies on different basis. It varies on a pot-by-pot basis, due to the segregation along the alumina distribution system. It varies over time, following switches of alumina supplies, but also at a higher frequency due to the maintenance performed on some of the alumina distribution system components and on handling policies.

An alumina flowability sensor was developed and industrially tested in order to estimate, in an on-line fashion, the alumina flowability. The sensor proved to be robust to the harsh smelting environment and provide reliable signals.

Improvements have also been made on the alumina delivering from the feeder pipe to the top of the bath surface. A small reduction in anode effect frequency has been demonstrated on a test group of pots.

This paves the way to real time optimization of alumina feed control parameters. It is believed that this would enable to achieve higher current efficiency, lower energy consumption and lower anode effects rate. Some work still needs to be done in this area.

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