Essential Readings in Light Metals: Electrode Technology for Aluminum Production.
Edited by Alan Tomsett and John Johnson.

From ***Light Metals 1985***, H.O. Bohner, Editor

POTLINING FAILURE MODES

M. Benjamin Dell, Consultant

144 Woodshire Drive
Pittsburgh, Pennsylvania 15215
USA

Summary

In aluminum smelting cells attempts to improve potlining life must deal with specific modes of failure observed in a particular potline. Knowing the type of failure is a prerequisite for making decisions on changes in design, materials or operation. Types of failures are classified by their location: in the bottom, side, shell and collector straps. Each failure mode is described along with the causes and suggested remedies.

Introduction

Once an aluminum potline has been installed and is operating it becomes desirable to improve potlining life. These improvements are sought through a series of changes in design, installation and operating practices. For guidance in making changes, anecdotal information, opinions, regression analyses or statistically designed experiments are frequently used. But experience shows that the best guidance is obtained through examination of shut-down cells in a carefully planned and executed autopsy program. Observation of the predominant types of failure and understanding their causes generally leads to effective remedial action.

Laboratory studies and some reports on cell autopsies have been published. However, no comprehensive summary of the various types of failures found in smelting cells is available. This paper is a compendium of what has been found in autopsies, and discusses briefly the chief types of failure, the mechanisms involved and possible remedial actions. While the sample is somewhat limited, it is based on examinations of cells in sixteen smelters both domestic and overseas.

The examinations usually involved a careful autopsy. Cells were cooled to room temperature without watering. The superstructure and metal pad were removed allowing observations on the top of the cell and the shell. A cross-section (usually transverse) was exposed by digging and observations and measurements of significant features were made. Samples from various locations were analyzed usually by semi-quantitative x-ray diffraction. Significant weaknesses and the failure types were noted. For convenience in this paper the failure types are arranged and discussed under the following categories: bottom, side, shell and strap connections. A diagram (Figure 1) illustrates the various terms used.

Bottom Failures

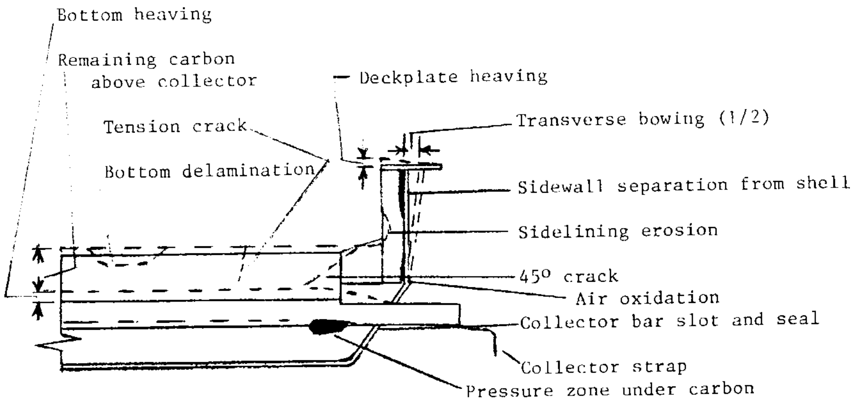
Failures in cell bottoms can be of the following types: heaving, cracks in blocks, gaps and cracks in tamped mix, potholes, erosion and delamination.

Heaving

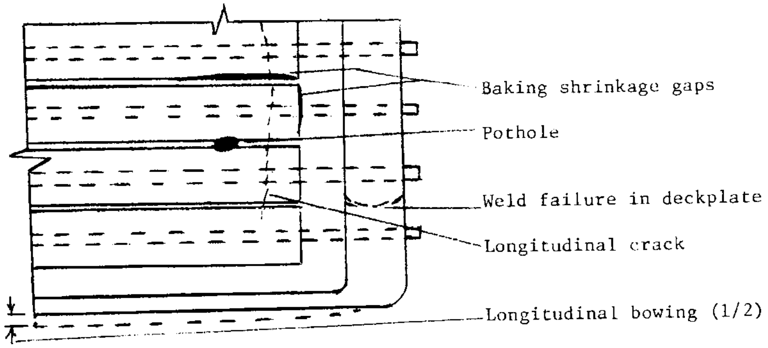
Heaving of the cell bottom is measured by the upward displacement of collector bars near the center of the cell. It can be as much as 150 mm. If the cell bottom is greatly distorted the cell may have to be shut down because of operating difficulties or leakage through heaving cracks.

Heaving of cell bottoms has two causes. The first is the lateral expansion of the carbon bottom caused by absorption of sodium. Laboratory studies show that after electrolysis starts, sodium is absorbed by the carbon lining causing it to expand (Rapoport and Samoilenko (1), Dell (2), Belitskus (3) and others). As the sodium enters the lining the top expands causing the lining to heave upwards (Waddington (4)). The upward movement is further increased by buckling action because of the resistance by the steel sides and end walls to lateral expansion of the carbon.

The second cause of heaving is pressure from underneath the carbon lining caused by two types of expansion reactions (Dell (5)). In the first an oxygenating gas reacts with cryolite and sodium which have penetrated through the carbon lining:



Transverse half-section



Top quarter of cell

Figure 1 - Potlining failure locations and terminology

$$2Na_3AlF_6 + 8Na + 2O_2 \longrightarrow 12\ NaF + Na_2O{\cdot}Al_2O_3 \qquad (1)$$

Volume change = 78%

In the second type the reaction is with the bottom insulation such as alumina or the mullite in firebrick:

$$2Al_2O_3 + 4Na + O_2 \longrightarrow 2(Na_2O{\cdot}Al_2O_3) \qquad (2)$$

Volume change = 138%

$$3Al_2O_3{\cdot}2SiO_2 + 8Na + 2O_2 \longrightarrow 3(Na_2O{\cdot}Al_2O_3) + Na_2O{\cdot}2SiO_2 \qquad (3)$$

Volume change = 190%

Presumably, as the reactions proceed the sodium is constantly replenished by diffusion from the metal pad downward through the carbon lattice or through the molten bath in the pores of the carbon. The oxygen derives from air which passes through the collector bar seals in the side shells. Because of these reactions a pressure zone forms under the carbon bottom. The location is determined by the freeze isotherm.

There are several remedies to be considered if heaving is a problem. Use of semi-graphitic blocks should reduce the amount of sodium absorption and the resultant expansion. For a semi-graphitic block the cathoding expansion measured in the laboratory was 0.1% compared with 0.8% for an anthracite block (Fujishima et al (6)). A further alternative is to use a soft insulation to absorb the lateral expansion of the bottom lining, or soft bottom insulation to reduce the effect of expansion under the bottom lining.

Percolation of bath and dissolved sodium to the bottom of the carbon blocks should be reduced by use of low-porosity blocks. Such blocks have been described (7) but no correlation with measurements of heaving has been published. Another approach is to reduce the amount of oxygen available for reaction by use of a better seal where the collectors pass through slots in the side shells.

The expansion forces underneath the carbon lining might be reduced by finding and using insulation resistant to attack by sodium and oxygen. A likely candidate for further test is a magnesite insulation described in recent Russian literature (8). Vermiculite and perlite slab insulation resistant to alkaline bath have been described by Tabereaux (9). Although such insulations can have an upper limit of over 1050°C, their successful use adjacent to bottom potlining has not been reported.

An approach sometimes used is to increase the bottom insulation. The mechanism probably involves a shift towards the sides of the freeze isotherm and the accompanying pressure zone. The upward pressure is then resisted more strongly by colder steel in the collector bars and there is decreased leverage due to application of the pressure closer to the "fulcrum", the sides of the bottom lining.

Cracks in Blocks

It should be noted that nowadays it is rare to find cracks that can be related to poor block quality. Rapoport has shown that rapid heating of blocks during start-up does not cause cracks in blocks (10). Unfilled cracks in the bottom of cells examined after shut-down are cooling cracks. However, cracks filled with bath or yellow aluminum carbide were presumably caused by forces during cell operation.

In block bottom cells generally only longitudinal cracks (parallel to the sides) are found, although Kure and Kowano reported transverse cracks (11). These are caused by heaving of the cell bottom which puts the top of the lining in tension. The strength of carbon is much lower in tension compared with compression. In addition, near the sides there is frequently found a longitudinal crack extending downward and inward - the so-called 45° crack or shelving crack. This is apparently a shear crack caused by increased upward pressure due to expansion forces below the carbon lining. As explained previously these forces are caused by reaction of cryolite, alumina or firebrick with sodium and an oxygen-containing gas in a pressure zone near the sides.

Both the 45° shear crack and tension cracks due to heaving can grow sufficiently to cause high iron in the metal or a tap out. The remedy is to reduce heaving as described previously.

Ear cracks in blocks are sometimes found at the base of the collector after pouring cast iron. These are due to thermal stresses in the irregular cross-section at this location. They can be eliminated by proper preheating before pouring the cast iron. Increased cast iron thickness should reduce the incidence of those ear cracks which may form during cell heat-up by transverse expansion of the collector bar and cast iron.

Gaps and Cracks in Tamped Mix

Gaps and some cracks are caused by shrinkage of the green carbon mix during bake-out of the newly lined cell. Changes in dimensions of the green mix have been studied in the laboratory. Much published data deal with dimensional changes of specimens after baking and cooling to room temperature. More realistic data for cathodes give measurements in a dilatometer obtained as the specimen was heated to operating temperature (Dell and Peterson (12), Belitskus (13) and Martirena (14)). These data show that depending on formulation, tamping and heating rate, the green mix usually contracts during baking, frequently after an initial expansion. The net shrinkage can be as great as 0.5 to 1.0%.

In tamped seams between carbon blocks, baking shrinkage of the tamped mix can cause gaps between mix and blocks. If these gaps are thin they normally fill with metal. Aluminum carbide then forms blocking further damage. Shrinkage along the long dimension of a tamped seam, or in some designs in the tamped mix at the outer edge of the bottom blocks near the sidelining can also cause baking shrinkage cracks or gaps.

In tamped monolithic bottoms, cracks occur because of contraction of the tamped mix on baking. The mechanism has been ascribed to shrinkage towards the points in the lining of initial current passage and heat generation with planes of weakness where adjacent shrinkage zones meet (Dell 15).

The remedy for baking cracks and gaps is to optimize for minimum baking shrinkage the mix formulation, tamping and baking. In block bottoms improvements can also be obtained by using tamped seams of minimum width to reduce the gap due to baking shrinkage or by elimination of tamped seams through use of very thin cemented joints.

Potholes

Potholes are aluminum-filled depressions shaped like inverted cones. They have bases up to about 100 mm in diameter. They can occur throughout monolithic bottom linings, but in block-lined cells they occur almost exclusively in the tamped seams (16).

Potholes are always on metal-filled cracks. A proposed mechanism involves a preferred current path through the metal-filled crack down to a collector. The local high current density combined with the magnetic flux produces a small whirlpool. Erosion of a pothole results from rapid motion of the metal combined with the abrasive action of suspended insolubles. Another mechanism involves the rapid flow of metal in the bottom across an obstruction or crack which also can result in a local whirlpool.

One remedy is to reduce the incidence of cracks or seam gaps in the cell bottom. In monolithic linings reduction of zones subjected to rapid initial baking (17) and resultant shrinkage cracks should reduce early failures through potholes. An increase in current efficiency frequently results in reduced incidence of potholes. This probably occurs because of reduced metal pad velocity.

Bottom Erosion

The bottom erosion rate is best calculated from the decrease in thickness of carbon measured above a collector bar. For comparative purposes the location of the measurement is usually at the center of the cell. Typically, erosion is about 25 mm/year, but values vary from about 10 to 100 mm/year. For a block bottom cell with about 275 mm of carbon above the collectors, a uniform erosion rate of 25 mm/year would correspond to a limit on lining life of eleven years.

The erosion mechanism was described by Hollingshead and Brown (18). It involves formation of aluminum carbide on the carbon bottom, transfer of the aluminum carbide first by dissolution in the metal pad and then into the bath. In the bath it reacts with an oxidizing gas such as CO_2 and the reaction continues.

Usually a high erosion rate is indicative of excessive metal flow rate or turbulence. High erosion rates have also been found with soft carbon bottoms, e.g., when graphite bottom blocks were used.

The erosion rate is chiefly controlled by mass transfer and is lowered when metal flow rate is reduced (18). Frequently, an increase in current efficiency, when accompanied by reduced metal flow will also be accompanied by a reduced erosion rate.

Bottom Delamination

Very rarely chunks of bottom lining break off and float to the surface. This can usually be traced to excessive pressure against the bottom from expansion in the insulation.

In addition, Quandt and Begany (16) observed disruption of cathode blocks due to high iron and sulfur in anthracite used for block manufacture. On exposure to sodium, Na_2S was formed from FeS with a large increase in volume.

Sidelining Failures

In this discussion sidelining failures are defined as those located in the lining above the bottom lining. In the absence of careful observation, such failures are sometimes mis-classified as bottom failures because of the location of the tap-out through the shell.

Erosion

The mechanism for erosion of sidelining is the same as for the bottom. After start-up the sidelining erodes until the wall temperature drops sufficiently to form a protective frozen coating of bath (Clelland, Keniry and Welch (19)). The thickness of the layer is determined by heat loss through the sides. An increase in bath temperature can cause the frozen layer to melt and expose the carbon to reaction with molten aluminum. The aluminum carbide which forms is more quickly carried into the bath (shorter path length) at the bath-metal level and this is where erosion is usually greatest and tap-outs occur. Melting of the frozen bath is promoted by rapid flow of bath and metal adjacent to the sidewalls.

Remedies include use of graphite or silicon carbide sidewalls. Graphite is used presumably because it is less reactive than carbon and its higher thermal conductivity should help formation of a frozen bath layer. Silicon carbide has a high thermal conductivity and is resistant to bath. However, if constantly exposed to molten bath and metal an increase of 0.01 Si may be found in the aluminum.

Oxidation

Carbon or graphite sidewalls can oxidize during heat-up if they are unprotected from contact with air. During operation a hole in the steel shell, such as a failed weld can lead to oxidation of the carbon adjacent to the shell. A poor seal of the collector bar hole in the side shell can lead to infiltration of air and oxidation adjacent to the shell of the carbon bottom and sidelining. Poor coverage of the top of the sidelining under the deckplate can result in air in-leakage and oxidation of the top of carbon sidelining.

Separation of Sidwall From Shell

In some cells the sidelining is found separated from the shell by a thick white deposit. In the extreme this deposit can grow progressively to over 75 mm and push the sidelining into the bath.

The mechanism (5) is believed to start with formation of an initial gap between the sidelining and the shell. The gap forms by oxidation of sidelining adjacent to the shell because of air infiltration under the deckplate or through the collector slot in the shell. The gap fills with bath which expands because of formation of sodium aluminate or by reaction of cryolite with sodium to form sodium fluoride. An additional reaction causing pressure within the gap is the formation of sodium carbonate from sodium and carbon dioxide.

The remedies involve preventing infiltration of air by adequate sealing under the deckplate and around the collector bar slot. Sometimes changes in operating practices are necessary since the problem may be caused by excessive bath height during start-up or during anode effect quenching (by lowering anodes) which in combination with excessive bath temperatures allows liquid bath to penetrate through gaps under the deckplate.

Shell Failures

Bowing

By transverse bowing is meant the increase in distance between the side shells after a cell is placed in operation. It is measured at the inside of the shell under the deckplates at the center of the cell. Longitudinal bowing is the corresponding measurement in the longitudinal direction. Transverse bowing can be as great as 200 mm and longitudinal bowing around 100 mm.

While some bowing originates in expansion of the steel shell during heat-up the chief cause is lateral expansion of the carbon bottom lining on absorption of sodium. Pressure and bowing from this expansion are observed immediately after the start of electrolysis (Rapoport and Samoilenko (1)). In autopsies crushed side insulation just above the collectors has been noted (15).

Strengthening of the cradle uprights can diminish the extent of bowing. However, this is usually accompanied by increased heaving to accommodate the lateral expansion in the bottom carbon lining due to sodium absorption. Better solutions include use of compressible insulation adjacent to the side and end shells and use of semi-graphitic bottom blocks which have reduced absorption of sodium and reduced expansion.

Weld Failures

Weld failures are sometimes observed in welded steel reinforcements on the ends and sides of cells and in deckplates near the ends of cells. These are all chiefly caused by lateral expansion of the bottom carbon lining and the same remedies apply as for bowing.

Deckplate Heaving

Frequently the inner edges of deckplates move upwards from 50 to 75 mm. The cause is probably the same as for sidelining separation from the sidewall. Alumina ore cover or bath materials enter into a gap between the deckplate and sidelining. These materials react with sodium and oxygen. The products have an increased volume and force the deckplates upwards.

The remedy is to seal adequately to prevent entry of these materials into gaps between the sidelining and the deckplates.

Strap Connections

Occasionally failures occur in the straps connecting the collectors to the ring bus. One type of failure occurs with fusion bonded connections. If these are allowed to overheat a brittle intermetallic compound forms. Overheating is usually due to the insulating effect of ore spillage onto the connection. The remedy is to reduce spillage, clean it out on schedule or use a bolted connection.

Another type of failure is due to corrosion of the collector straps. This occurs chiefly in long-lived cells due to cumulative exposure to sodium (actually sodium carbonate) from leakage through the collector seals. Improvement of the seals is necessary.

Conclusions

The types of failures found on examination of failed cells are each caused by mechanisms characteristic for that individual type of failure. The remedy has to be one that responds to the particular mechanism responsible. The remedy must also be acceptable from an operations and economic viewpoint.

References

1. Rapoport, M. B., and Samoilenko, V. N., Tsvet. Metal., 30, No 2, 44-51 (1957).
2. Dell, M. B., Extractive Metallurgy of Aluminum, G. Gerard, Ed., Vol 2, p. 403, Interscience Pub., New York (1963).
3. Belitskus, D. L., Light Metals 1977, Vol. 1, p. 317.
4. Waddington, J., J. Metals, 29 (9) (1969).
5. Dell, M. B., Met. Trans. B, 15B, 277 (1984).
6. Fujishima, O., Takasawa, M., and Wakaizumi, K., Light Metals 1982, Table 1, p. 561.
7. Etzel, K., Brandmeir, F., Aeschbach, P., and Freidli, H., Light Metals 1983, p. 885.
8. Slavin, V. V., Kamenev, B. A., and Bezuklahnikova, L. A., Tsvet. Metal. 56, No. 5 (1983). (Vol. 24 of English Translation, p. 42).
9. Taberaux, A. T., Light Metals 1982, p. 571.
10. Quoted in Slavin, V. V., Tsvet. Metal, 50-53 (9) (1979).
11. Kure, T. and Kawana, K., Light Metals 1978, p. 255.
12. Dell, M. B., and Peterson, R. W., Met. Trans, 4, 2077 (1973).
13. Belitskus, D., Light Metals 1983, p. 741.
14. Martirena, H., ibid p. 749.
15. Dell, M. B., J. Met., 14 (3) (1967).
16. Dell, M. B., Peterson, R. W., and Rumble, J. N., J. Met., 55 (9) (1968).
17. Johnson, W. L., Light Metals 1971, p. 437.
18. Hollingshead, E. A., and Brown, J. A., Light Metals 1982, p. 625.
19. Clelland, C. H., Keniry, J. J., and Welch, B. J., ibid p. 299.