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BAR TO BLOCK CONTACT RESISTANCE IN ALUMINUM REDUCTION CELL CATHODE ASSEMBLIES

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Abstract

Contact resistance between the collector bar and cathode block has been previously estimated at 10 Ωmm^2 contributing roughly 100 mV to cell voltage. This paper proposes four mechanisms as contributors to high contact resistance through low contact pressure and large scale intermittent contact. These mechanisms are: temporary bowing of the bar during solidification of cast iron joints, shrinkage of the bar during the phase change from ferrite to austenite, mismatch of iron and carbon surface texture due to axial thermal expansion, and reduced contact pressure due to creep in the steel bar.

Introduction

The floor of the cavity in modern aluminum reduction cells is lined with cathode assemblies, consisting of carbon blocks joined to current collector bars. (see Figure 1) Cathode voltage drop (CVD) has contributions from the block, the bar, and the joint that connects them as previously reported [1] and as shown in Figure 2.

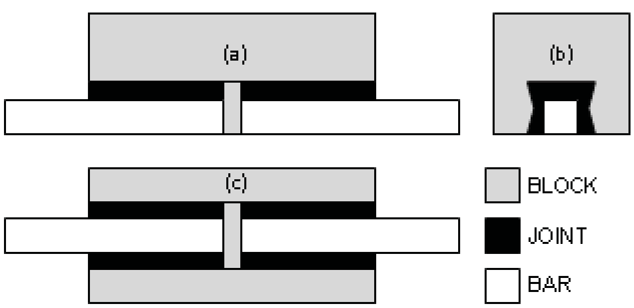

Figure 1. Sketch of typical cathode block assembly: (a) side cut away, (b) end view, (c) bottom view.

The electrical resistivity of typical joint materials (cast iron in particular), coupled with typical nominal current densities across the joint, should lead to inconsequential voltage drops within the joint material itself. We therefore conclude that the joint resistance is almost completely due to contact resistance, or lack of contact. In the case of cast iron joints, contraction around the bar during rodding leads us to focus on contact with the surface of the carbon as the primary source of resistance, rather than the surface of the collector bar.

At 100 mV, the electrical contact resistance of the joint represents at least 2 % of power consumption for a modern smelter. For this reason it behooves us to examine the likely contributors to that resistance.

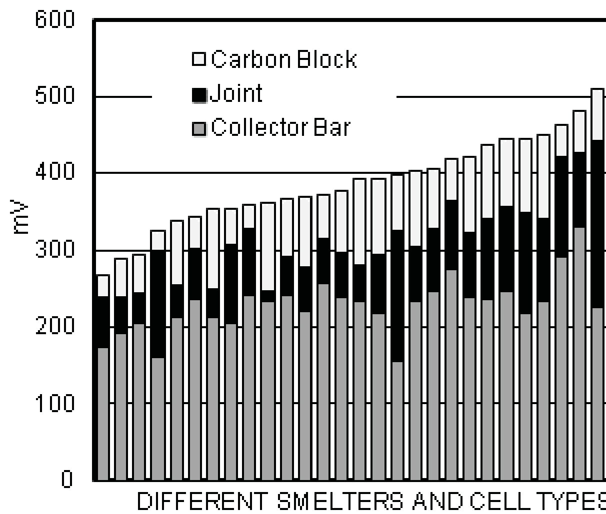

Figure 2. CVD components for different plants, cell technologies, and joint materials. Joint voltage was determined by tuning a model's joint contact resistivity to make the calculated CVD match each plant's measured CVD. The averages of all joint voltages and resistivities are 100 mV and 10 Ωmm^2, respectively. No clear advantage between different joint materials was evident.

Bar Bowing During Rodding With Cast Iron

When cathode assemblies are rodded with cast iron, it is common practice to pour the iron to cover the sides and bottom of the bar, but not the top. (See Figure 3.)

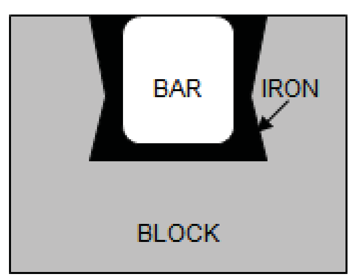

Figure 3. The cathode assembly, upside down for rodding. In most practices, cast iron does not cover the bar, resulting in undesirable asymmetric heating of the bar by the hot iron.

This practice causes uneven heating of the bar, with the bottom temporarily becoming much hotter than the top. The asymmetry suggests one mechanism contributing to contact resistance as depicted in Figure 4.

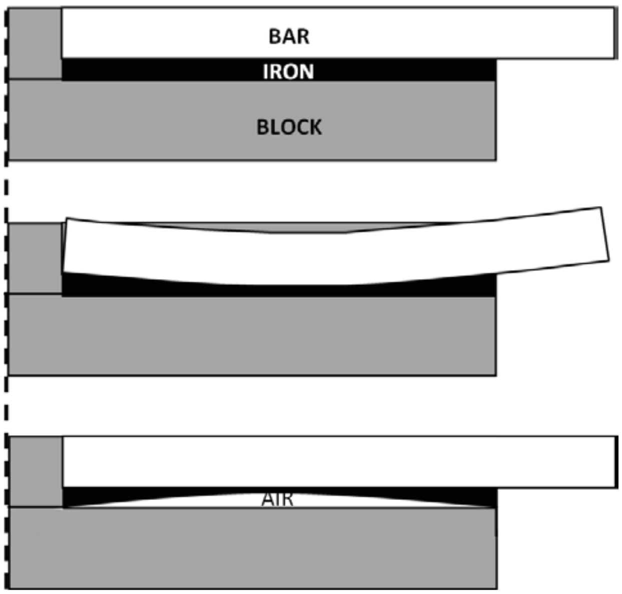

Figure 4. Half of bar-block assembly. Molten cast iron heats the bottom of the collector bar (top). The iron freezes with the bar bowed up at its ends (middle). As temperature evens out the bar straightens leaving a lens shaped air gap (bottom).

Thermal modeling of this process was used to estimate the temperature gradients in the bar and the solidification time for the iron. Subsequent thermo-mechanical calculations yielded predictions for the resulting radius of curvature and out of flatness in the bar, assuming elasticity. (See Figure 5)

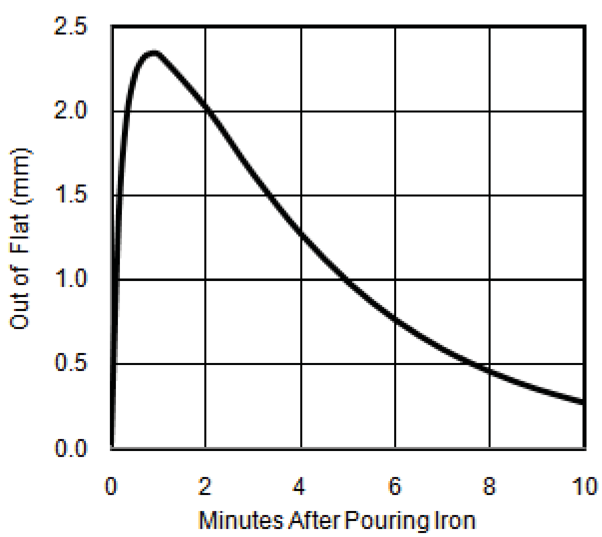

Figure 5. Predicted out of flatness due to bowing of a collector bar after pouring cast iron.

Both the predicted solidification time and the time of maximum out of flatness occur near one minute after pouring. So, we expect that a lens shaped air gap could result from longitudinal changes in iron thickness being locked in as the iron solidifies. This was investigated by autopsying two unused cathode assemblies. The iron thickness under the bar was measured down its length and found to indeed vary in thickness, as expected. (See Figure 6)

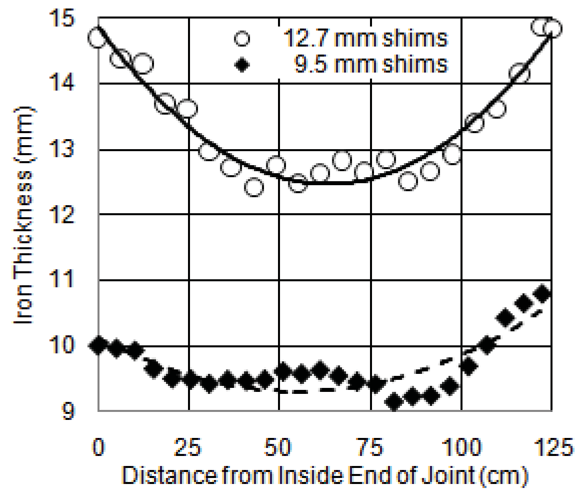

Figure 6. Autopsies of unused cathode assemblies showed anticipated longitudinal thinning of the iron.

When inspecting Figure 6, we see that the bar with thinner shims holding it off the bottom of the cathode slot, and thus thinner nominal iron thickness, had less bowing. This is consistent with our proposed mechanism, as thinner shims should allow less iron under the bar, with less heat content, and less resultant bowing of the bar.

Creep of Steel at Operating Temperatures

Collector bars are subject to creep at temperatures near 900 °C seen during cell operation. However, commonly available creep data for carbon steel ends near 650 °C [2]. At cell operating temperature the creep strength is far below what is needed for conventional construction, and creep deformation is far too slow to be of interest in manufacturing processes such as rolling and forging. Wilkening and Winkhaus [3] do provide us with several data points, including approximately 0.002 %/hr creep at 900 °C and 1.3 MPa. That rate corresponds to almost 1% creep in three weeks. We therefore expect that effective contact pressures in the joints of cells that operate for several years must be appreciably lower, as 1.3 MPa could not be sustained for long.

Steel Phase Change

A typical carbon steel collector bar exhibits greater thermal expansion than the carbon cathode block. (See Figure 7.) This situation causes a tightening of the joint at cell start up, as the bar's width grows faster than the surrounding slot in the block.

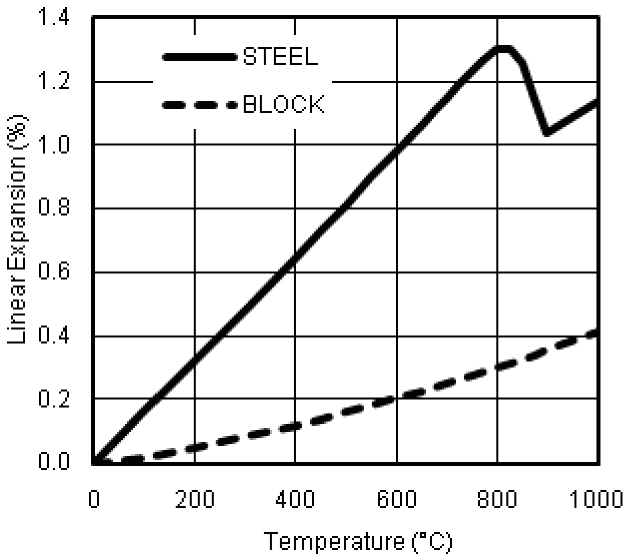

Figure 7. Nominal linear thermal expansion for a carbon steel collector bar and a carbon cathode block. Note the contraction of steel starting near 800 °C.

That is one reason why collector bars are typically preheated before rodding with cast iron. The thermal expansion of the bar results in a thinner layer of iron, leaving the joint loose at room temperature, and preventing an excessive interference fit that could crack the block during cell start up.

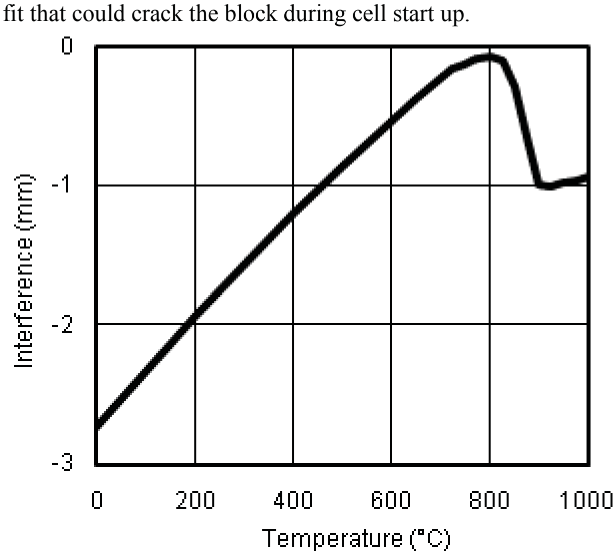

Figure 8. A representative calculated interference fit between the width of a carbon steel collector bar and a carbon cathode block. Note the loosening as interference drops above 800 °C. In this example all values are negative, i.e. no interference.

However, the thermal expansion of the steel bar (and of cast iron) is not monotonic. In the vicinity of 800 °C, the steel undergoes a phase change from ferrite to austenite during which the steel contracts. A plot of one calculated interference fit, as a function of temperature, is shown in Figure 8. The key feature of this plot is that the joint's tightest condition, and thus its highest stress, occurs near 800 °C. Collector bars typically operate near 900 °C. So, the joint must start with enough looseness to survive its greatest interference fit at 800 °C, and then operate in a looser state near 900 °C.

Mismatch of Surface Texture

Solidification of cast iron against the carbon surface of the cathode slot can result in macroscopic asperities, as shown in Figure 9.

Figure 9. Example of cast iron texture on the surface that solidifies against the carbon slot in a cathode block.

If the carbon is not smooth, some features may correspond to machining marks in the surface of the carbon, while others are simply a result from solidification and have no corresponding shapes in the carbon. In either case, the materials will have different axial thermal expansion. This suggests a mismatch between carbon and iron asperities on a macroscopic scale.

Discussion

The mechanisms described above are plausible explanations for large and non uniform contact resistance in the bar to block joint. These different sources are spread over the time frames of cathode rodding, start up, and operation so that eliminating them all at any one stage would be difficult.

These mechanisms and the estimated resistivity of 10 Ωmm^2 suggest that electrical contact across the joint is intermittent and/or occurs at lower contact pressures than are commonly investigated at cell operating temperatures [4, 5, 6]. Testing of iron to carbon contact resistivity over small areas with uniform contact pressure may be less appropriate than has been previously assumed, when considering the cathode joint.

References

1. R. Beeler, "An Analytical Model for Cathode Voltage Drop in Aluminum Reduction Cells", Light Metals 2003, 241-245.

2. H. E. McGannon, ed., "The Making, Shaping and Treating of Steel", (United States Steel) 9th edition, 1971, 1199.

3. S. Wilkening & G. Winkhaus, "Material Problems in Electrowinning of Aluminium by the Hall-Heroult Process", *J. Applied Electrochemistry* 19 (1989) pp 596-604.

4. M. Sorlie and H. Gran, “Cathode Collector Bar-to-Cathode Contact Resistance”, Light Metals 1992, 779-787.

5. D. Richard et al., “Carbon to Cast Iron Electrical Contact Resistance Constitutive Model for Finite Element Analysis”, *J. Materials Processing Technology* 132 (2003) 119-131.

6. F. Hiltmann et al., “Influence of Temperature and Contact Pressure Between Cast Iron and Cathode Carbon on Contact Resistance”, Light Metals 1996, 277-283.