Light Metals 2013 *Edited by: Barry Sadler*
TMS (The Minerals, Metals & Materials Society), 2013

OPTIMIZATION OF THE CATHODE COLLECTOR BAR WITH A COPPER INSERT USING FINITE ELEMENT METHOD

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Keywords: Cathode, Collector Bar, Hall-Héroult, Finite Element

Abstract

A finite element model of a cathode assembly including a copper insert inside the collector bar was developed. This thermo-electro-mechanical model includes interfaces to simulate the contact between different materials. In order to optimize this model, the authors propose an economic analysis based on the electrical operating cost, the relining cost and the life expectancy of a cell. The geometry of the model is subsequently varied in order to generate a multidimensional response surface based on these economic criteria. Results indicate that substantial economies could be achieved by reducing the resistivity of the collector bar and improving contact at the interface. Also, this model provides some insight in the contact between the different materials of the cathode assembly and its effect on cell performance.

Introduction

The present paper concerns aluminum production using the Hall-Heroult process. This large scale multi-physic operation makes experimentation both complex and expensive. This is why the field has been the subject of numerous modeling efforts. A few thermo-electro-mechanical models were developed in the recent years to simulate contact between the different materials of the cell. Goulet's thesis [1] studied the thermo-electro-mechanical contact between different materials within the cell. He developed the contact aspect of the FESh++ library [2], a REGAL in house finite element toolbox. As a validation model, Goulet studied the preheating phase of a P-155 cathode. Dupuis [3] presented a thermo-electro-mechanical ANSYS based application for the design of cathode collector bar slots. The model does not have an initial gap at the interface. Instead, the temperature map is initialized at the values measured during the cast-iron solidification. While this simplifies the model, it affects the contact pattern at the interface. The present model includes an initial gap in order to capture the effect of thermal expansion on the contact between the different materials.

Problematic

The aluminum industry is interested in reducing its energy consumption as it represents about a third of the aluminum production costs. This can be achieved by increasing current efficiency or by reducing voltage drop. Modern cells achieve around 96% of current efficiency [4]. The cathode assembly is responsible for around 10% of the cell voltage drop. The aluminum industry is also interested in increasing the life expectancy of the cells as their relining cost about 300000$. As an order of magnitude, a 30mV voltage drop reduction saves about 5000$/years/pot. An increase in the cell life expectancy of 1 year amounts to about the same savings.

Objectives

1. Reduce the voltage drop through the cathode.
2. Increase life expectancy of the cell.
3. Optimize and compare cathode assembly designs using finite element modeling.
4. Study the energy loss through the cathode.

Assumptions

1. Current efficiency is considered constant.
2. The effect of changes in the cathode design on other aspects of the cell such as the anode to cathode distance, the magnetic field and the bath stability is neglected.
3. All voltage drop savings can be captured.
4. The cell performance does not vary over its lifespan.
5. Mechanical behavior is purely elastic.

Finite element model

Alcoa has patented a cathode design containing a copper insert in the collector bar (Patent WO/2001/027353). Figure 1 illustrates this patent.

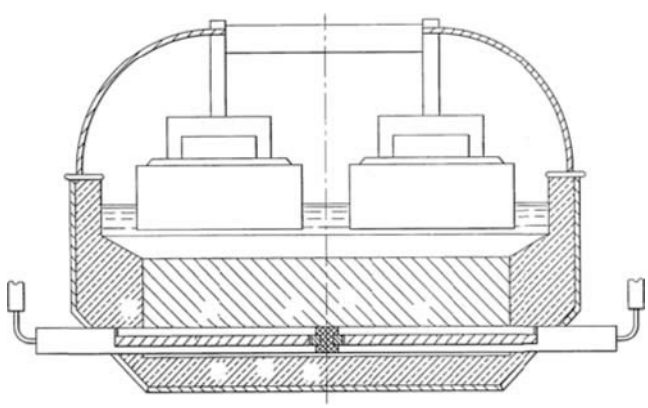

Figure 1: Patent WO/2001/027353

This design is used as a benchmark for the present work. A thermo-electro-mechanical finite element model with interfaces was developed in order to simulate the contact between the different materials. The meshing is done with ANSYS 14.0 and the model is solved using FESh++. Thanks to the double-symmetry of the cathode design, only a quarter of it is modeled. Figure 2 shows the model with double symmetry.

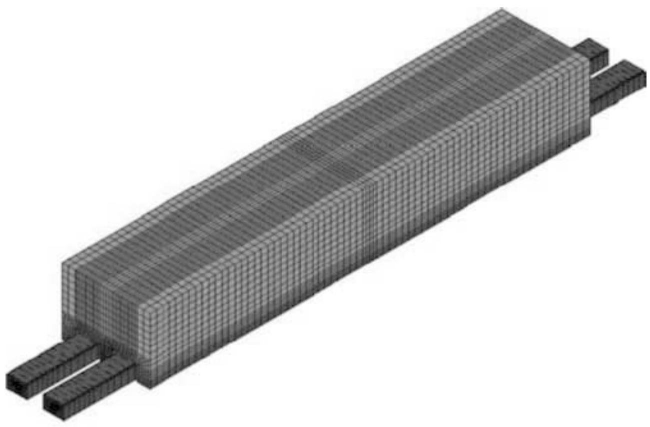

Figure 2: Finite element model with double symmetry

The model is purely elastic and therefore, stress relaxation due to plasticity and creep is not captured. The cathode is typically composed of a rectangular carbon block in which slots are machined on the inferior surface. Steel bars are then sealed in these slots using melted cast-iron. The temperature gradient caused by pouring the cast-iron will induce a curvature in the bar. Then, contraction and solidification creates an asymmetrical gap at the carbon/cast-iron interface. Figure 3 and 4 illustrate this phenomenon.

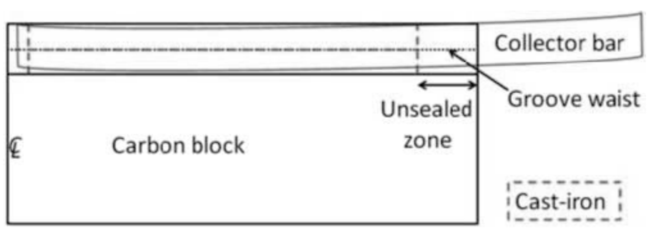

Figure 3: Curvature of the collector bar during sealing

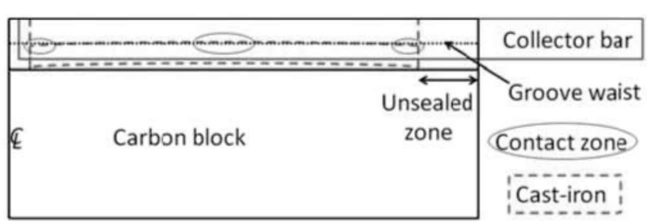

Figure 4: Cathode assembly after solidification

This effect can be reduced by preheating the assembly. At operating temperature, the material dilatation partially closes the gap but, some analytical calculations [5] and finite element modeling [4] indicate that contact pressure is sparse and low. This is supported by industrial high cathode voltage drop measurements. Electrical resistivity at the interface is function of pressure and is based on Hiltmann's results [6]. Figure 5 shows the voltage drop through the model.

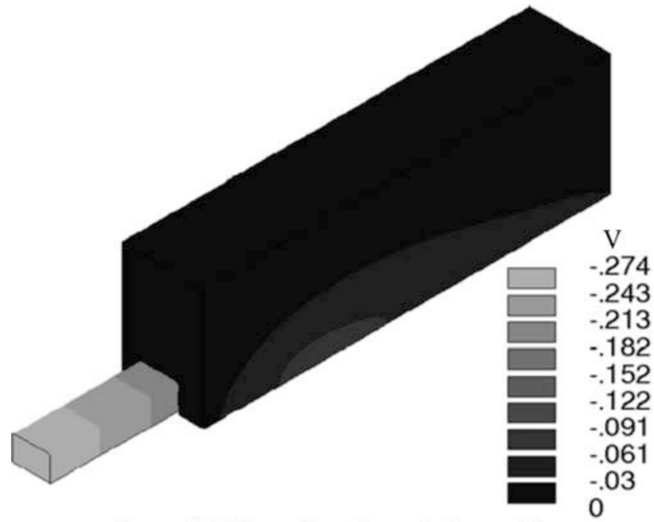

Figure 5: Voltage drop through the model

The initial gap between the cast iron and the carbon slot was calculated analytically. The asymmetry in the solidified cast-iron is not included in the model. This was done because of an incomplete study of the solidification process and in order to simplify the geometry of the model. The voltage drop through the cathode strongly depends on the contact at the interface. Since the model does not consider the curvature in the bar, the initial gap must be slightly reduced in order to achieve the anticipated voltage drop. Figure 6 presents the pressure distribution between the carbon and cast-iron for the benchmark case.

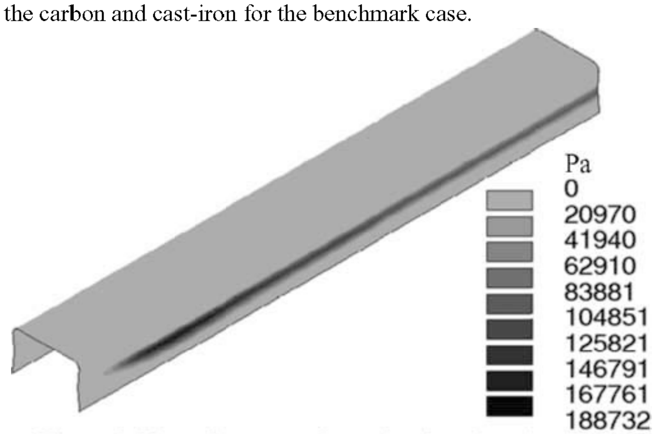

Figure 6: Normal stress at the carbon/cast-iron interface

The interface's hourglass shape allows the carbon wings on the sides of the slot to hold the collector bar while the cooled cathode assembly is turned upside down and transported to the cell. This configuration results in very localized contact zones causing high current densities and therefore, important voltage drop at the interface.

In operation, the carbon blocks are constrained and compressed by the shell. This compression is important because it affects contact pressure at the carbon/cast-iron interface. The only available data regarding the strength of this compression comes from gauges installed on the longitudinal trusts reinforcing the shell (Alcoa internal report). From these measurements, it is possible to estimate that a pressure of around 1 MPa is generated on the block face. This value also matches the compressive strength of the crushing bricks present in the insulation between the shell and the carbon block. The use of mechanical contact interfaces on the cathode block sides was initially considered as it provides a more reactive form of boundary. However, due to the complexity of the different phenomenon occurring in the cell that affect stress generation such as cell bending, ramming paste baking process, bath infiltration, sodium expansion, uneven thermal expansion, plasticity, creep and crushing, a simple 1 MPa pressure was applied on both side faces of the block. The cathode assembly needs to be mechanically supported while allowing the curvature and the lifting the collector bar in the slot. A mechanical foundation was chosen for this purpose. Both the block and the bar are supported by the foundation. Interpenetration at the foundation is limited to 0.1 mm. This prevents repercussions on the carbon/cast-iron interface. Figure 7 shows the normal pressure along the steel to copper interface for the benchmark case.

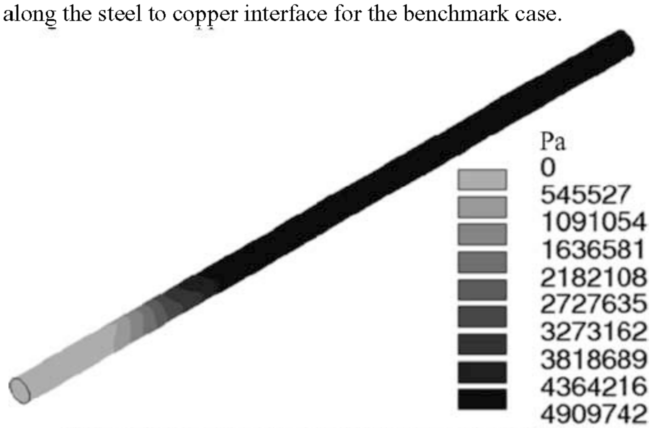

Figure 7: Normal stress at the steel/copper interface

The section of the copper rod outside the cathode block is cooler. This result in smaller thermal expansion and no contact is achieved in this section of the interface. Contact is however achieved between the tip of the rod and the bottom of the rod hole in the model. The utility of extending the copper insert outside the cell depends on the capacity of current to exit the rod at its extremity.

Voltage is zeroed on the carbon block top surface where the molten aluminum's low resistivity ensures a current redistribution. Current density and thermal flux are imposed at the extremity of the collector bar. During operation, a crust of frozen bath forms on the side-lining of the cell and occasionally extends on top of the cathode block. This added insulation locally reduces thermal and electrical conductivity. Due to the inconsistency of the phenomenon, it was not considered in the model. The formation of alumina patches or muck on the top of the carbon block near the center of the cell is another irregular phenomenon. It has a negligible effect on current density and voltage drop as current density is small in this portion of the cell and is therefore not considered in our model. Heat balance of the model is controlled by imposing convection coefficients on the boundaries of the model. Material properties are function of temperature. Due to a lack of data, material properties are for virgin material except copper electrical resistivity which is increased to take into account the gradual iron migration over the life of the cell [8]. The thermal expansion of steel and cast-iron is characterized by a phase change contraction around 800 °C. The collector bar operates near this temperature and this contraction greatly affects contact at the interfaces.

Current entering the carbon block near its extremities encounters less resistance than current entering the block near the centerline because it skips a long section of the collector bar. The current density is therefore greater near the extremities of the block. The intensity of this current concentration is governed by the vertical to horizontal resistance ratio. All the current must go through the vertical resistance (carbon block and interface resistance) in order to reach the collector bar. Horizontal resistance (collector bar resistance) varies depending on the position where the current enters the block. Graphitized carbon blocks where introduced for their lower electrical resistivity. However, graphitized carbon block low resistivity reduces the vertical to horizontal resistance ratio [7]. This increases maximum current density and reduces the life expectancy of the cell. Figure 8 and 9 illustrate the current lines and resistivity of semi-graphitic and graphitized cathodes respectively.

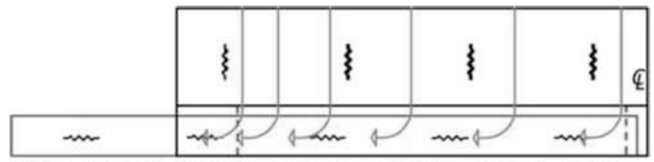
Figure 8: Semi-graphitic cathode resistivity and current lines

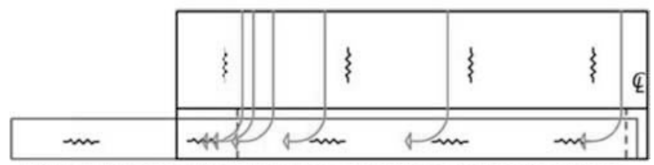
Figure 9: Graphitized cathode resistivity and current lines

Reducing electrical resistance of the collector bar inside the slot increases the vertical to horizontal resistance ratio and therefore even current density. The introduction of the copper insert design increased average life expectancy of the cells by 500 days. Figure 10 illustrates current lines in the benchmark model.

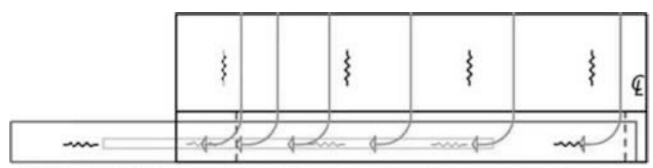
Figure 10: Benchmark cathode resistivity and current lines

Figure 11 presents current density on the top of the carbon block for the benchmark case.

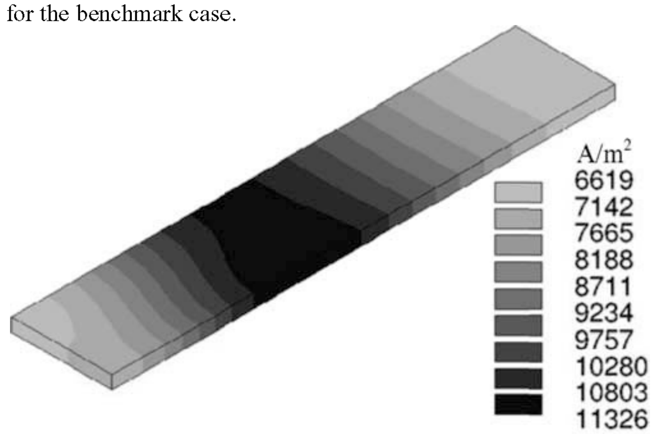

Figure 11: Current density on top of the cathode block

Figure 12 presents a typical cathode block erosion map.

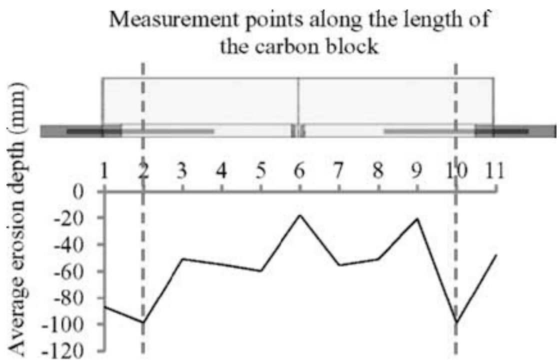

Figure 12: Cathode block erosion map

The position of the maximum current density does not precisely relate to the position of maximum wear of industrial cathodes. This could be explained by the effect of erosion on the current density over the life of the cell.

Economic analysis

The cathode optimization proposed in this paper is based on an economic analysis, combining electrical and relining costs. The electrical cost is varied with the voltage drop through the cathode. The relining cost is based on the volume of materials and a fixed labor price. This relining cost is thereafter converted to a 12% interest rate annuity over the average life expectancy of the cell. The life expectancy of the cell depends on numerous factors and is difficult to predict. However, the carbon block erosion is the desired and most common cause of failure. There is a strong correlation between maximum current density on top of the carbon block and life expectancy of the cell. A linear dependency between erosion rate and maximum current density was therefore developed based on industrial values in order to assess life expectancy of the cell. Figure 13 presents the equation governing this dependency.

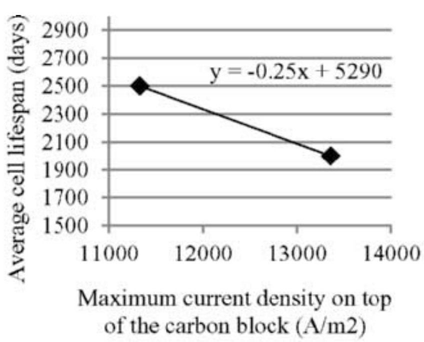

Figure 13: Lifespan as a function of maximum current density

The optimization is furthermore bounded by 2 other considerations. First, stresses in the carbon block must be kept under the cracking strength which is about 5 MPa [9]. The carbon wings are particularly sensitive to cracking. Second, temperature of the bath must be maintained around 960°C for the electrolysis to occur. Heat loss must therefore be limited. A maximum temperature of 400°C at the extremity of the collector bar is set as a maximum tolerable value (benchmark temperature is 300°C).

Optimization

The optimization is limited to the collector bar and its slot. The proposed solution must be applicable to the current industrial cell and cathode blocks. A new cell design is not pursued. Each of the dimension of interest were initially varied one by one in order to quantify their effect on the result and to determine data range. Subsequently, relevant dimensions were varied together in order to generate a response surface. Figure 14 illustrates some of the dimensions to be optimized.

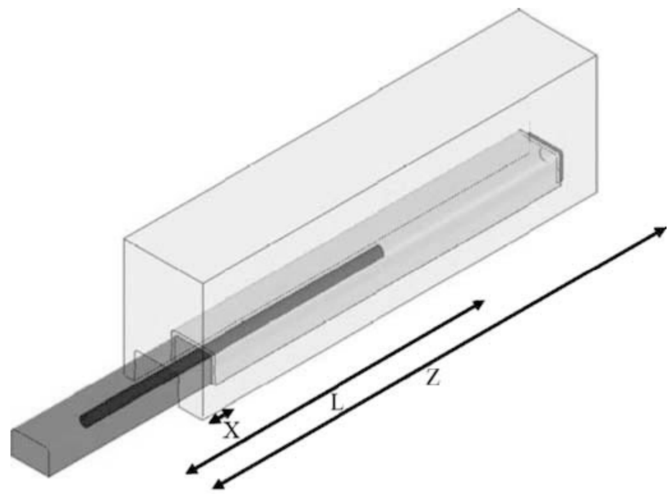

Figure 14: Benchmark design dimensions

Results

The following graphs present the economic analysis results as a function of the different dimensions optimized:

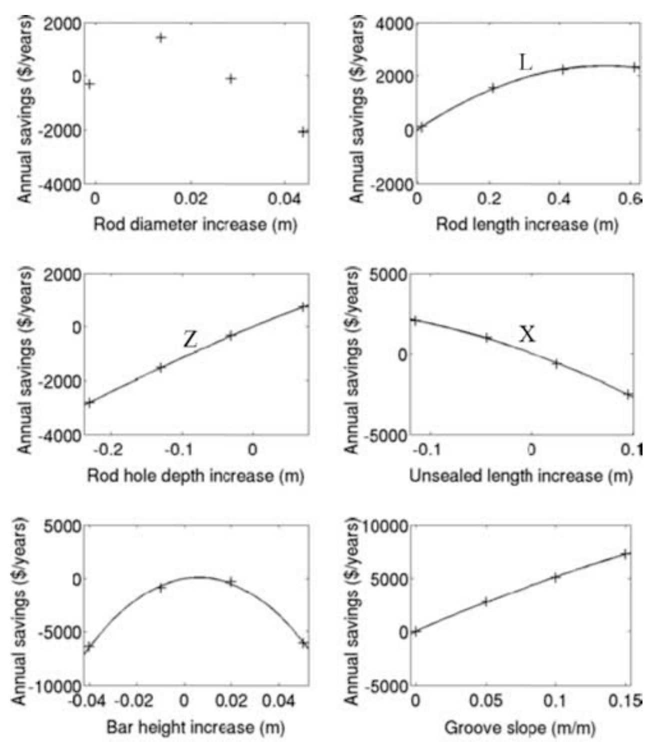

Figure 15: Economic analysis graphs

Table 1 contains the optimization results.

Table 1: Optimization results

Dimension	Voltage drop	Life expectancy	Relining cost	Savings
	mV	days	$	$
Rod diameter	-13	0	+9500	+1000
Hole depth (Z)	-7	0	+1400	+1100
Rod length (L)	-3	+180	+8500	+2500
Unsealed length (X)	-10	+40	+100	+2400
Optimized rod	-44	+470	+23900	+12100
Dimensions optimized with a planar interface:				
Planar interface	-72	-432	0	+2900
Bar height	0	0	0	+2900
Bar width	-103	+152	+3100	+19300
Bar slope	-83	-230	+11100	+8100

Results indicate that an overall increase in the amount of copper used is economically beneficial. Copper reduces the resistivity of the collector bar. It is particularly efficient near the carbon block extremities where current is maximum and temperature is high [5].

Increasing the length of the copper insert (L) evens current density by increasing the vertical/horizontal resistance ratio. It has a limited effect on voltage drop as the current density in the collector bar near the center of the block is small.

Increasing the depth of the copper rod hole (Z) reduces the voltage drop through the cathode. It is highly effective since current density is maximum in this section of the collector bar. This is conditional to contact being achieved at the tip of the copper insert. High thermal conductivity of copper causes higher heat loss however which is a limiting factor.

During the rodding operation, a dam is positioned near the slot's outside extremity in order to leave a part of the interface free of cast-iron (X). Thermo-electrical models typically take into account the interface by applying a fixed resistivity on the entire interface in order to match industrial cathode voltage drop. This simplification induces a high current density concentration in the extremities of the carbon block as most of the current crosses the interface there. The introduction of an unsealed zone in this type of model evens out current density and also displaces the maximum current density away from the block edge where the joint with ramming paste is a weak point in the lining. In the thermo-electro-mechanical model, current must cross the interface where contact is established. The introduction of an unsealed zone in this model reduces the already limited contact surface and therefore increases both voltage drop and maximum current density. The present results therefore suggest abandoning this practice.

Planar interface

It was observed that 25% of the cathode voltage drop is caused by the poor contact between carbon and cast-iron [5]. Improving the quality of contact would significantly reduce cathode voltage drop. It would however reduce the vertical/horizontal resistance ratio and therefore increase current density concentration. The current slot hourglass shape keeps the collector bar from falling while the assembly is transported to the cell. The use of a planar interface was therefore studied keeping in mind that such a design would require a new approach for transporting and positioning the cathode assembly in the cell. Results indicate that the gains in electrical costs outweigh the loss in life expectancy. Figure 16 presents the pressure distribution between the carbon and cast-iron for the planar interface design.

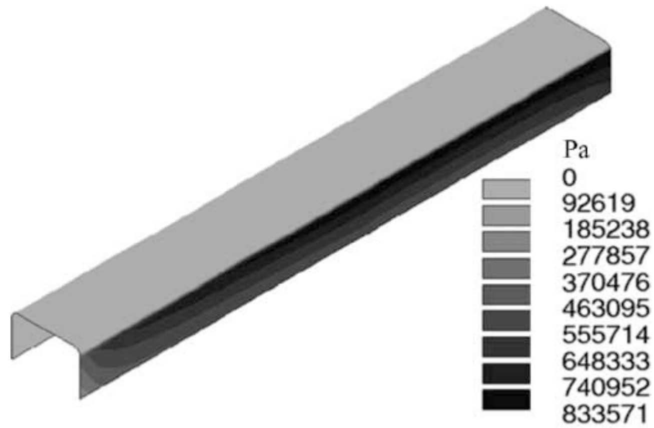

Figure 16: Normal stress on planar interface

Increasing the height of the collector bar reduces the resistivity but it also reduces carbon thickness over the bar and therefore affects life expectancy of the cell. The optimization validates the currently used dimension.

Optimizing the collector bar width is a balance between the bar electrical resistivity and the interface electrical resistivity. A wider bar is less resistive but the resulting reduction in the wing thickness limits pressure at the interface. Some smelters are using cathode assembly with one wide collector bar per block. This configuration is outside the scope of this paper. Figure 17 shows the principal stress in the carbon block for a 175mm width collector bar.

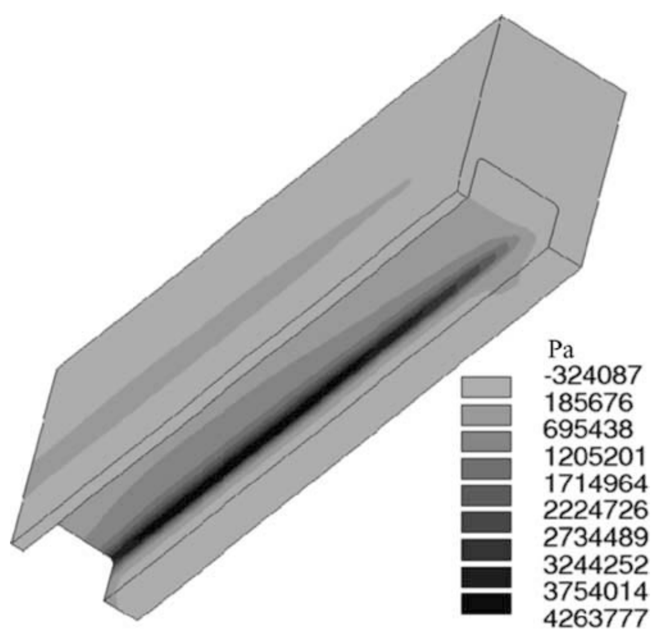

Figure 17: Principal stress in carbon

Patent WO/2007/118510 proposes a slot of varying depth in order to even current density. The carbon layer over the collector bar is gradually reduced toward the center of the carbon block so that the increasing collector bar resistance is compensated by a reduced carbon block resistance. Figure 18 illustrates this design.

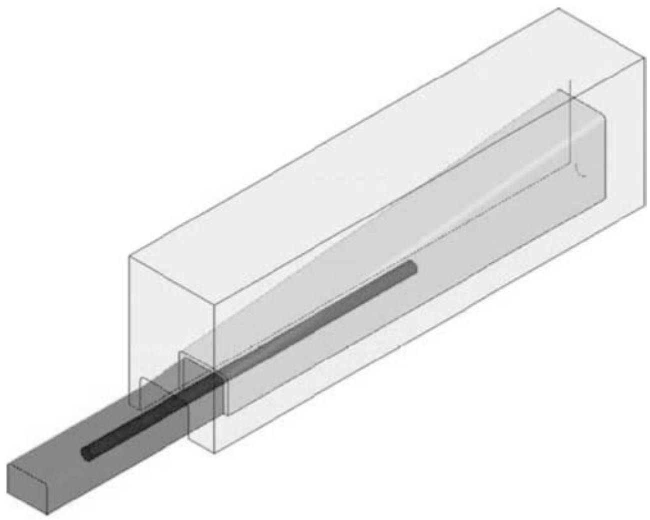

Figure 18: Slot of varying depth design

This promising solution was analyzed. The results suggest that a very steep slope is optimal. However, the resulting reduction of carbon thickness over the collector bar toward the centerline presents a risk of early failure in case of erosion in this zone. A deep slot also significantly increases stresses in the wings.

The response surface optimal design with regards to the copper insert suggests savings of 12900$/years/pot.

Conclusion

A thermo-electro-mechanical finite element model with contact interfaces was developed. Results show sparse and low pressure contact at the carbon/cast-iron interface. Moreover, no contact is achieved in the section of the copper/steel interface outside the carbon block.

Overall, the optimization favors a reduction of the collector bar resistivity which both reduces electrical cost and increases lifespan of the cell at the expense of increasing relining cost. The analysis suggests that the presence of the copper insert is economically beneficial. Patent WO/2007/118510 is economically beneficial. A planar interface is viable only if a new method for installing the assembly in the cell is developed.

There is still uncertainty regarding the interface initial gap to be used in a finite element model. An in depth study of the casting process is suggested. The impact of a new design on the other aspects of the cell, including anode to cathode distance, magnetic field and capacity to capture the saved voltage drop need to be investigated.

Acknowledgments

The authors gratefully acknowledge the financial support provided by Alcoa Inc. and the Natural Sciences and Engineering Research Council of Canada. A part of the research presented in this paper was financed by the Fonds de recherche du Québec - nature et technologies by the intermediary of the Aluminium Research Centre – REGAL. We also thank Claude Gauthier for his expert advice.

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