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DEVELOPMENT OF A NEW APPROACH TO INCREASE THE ELECTRICAL PERFORMANCE OF ANODIC ASSEMBLIES

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Abstract
The electrical resistance of an electrolytic cell requires a voltage drop of about 4.5 V for a current of 300 kA of which 7% is attributable to the anode assembly. Reducing this voltage drop is one of the most challenging research topics for the aluminum industry. Over the past decades, there has been much research on the minimization of this loss using the same assembly configuration. In this work, a new approach, which consists of inserting elements into the carbon paste during the anode production, was developed. This approach would provide a significant reduction in the voltage drop mainly through the improvement of the contact quality at the anode connection and the current distribution in the anode. Laboratory tests simulating the baking as well as the operation of small-scale assembly were carried out to estimate the resistance. The results demonstrate that it is possible to decrease the resistance at the anode connection under the conditions similar to those used by industry.

Introduction
The aluminum production requires a considerable amount of electrical energy to supply the necessary electrons to the process. The electrical resistance of an electrolysis cell involves a potential loss of about 4.5 V witch 1.18 V is theoretically necessary for the reduction reaction. The remaining 2.7 V is mainly associated with the resistance of the electrolyte, electrodes (anode and cathode assemblies) and conductors [1]. Among these components, the anode assembly itself represents a loss of about 300 mV. It is believed that there is a promising potential to improve the electrical performance of the cells by optimising the anode assembly design.

As shown in Figure 1, the anode assembly used in the Hall-Héroult process consist of a carbon anode (1) into which steel stubs (2) are inserted. The stubs are joined together by a steel crossbar (3) which is then connected to an aluminum rod (4) using a clad (5). To fix the stub to the carbon block, molten iron is cast in the preformed stub holes creating the connector or thimble (6). This assembly mechanically supports the anode and conducts heat and current to the carbon block.

Problem Statement
In a conventional design (see Figure 2), a cylindrical stub is inserted into a slightly conical stub hole. Once the cast iron solidifies, a gap forms at the cast iron to carbon interface since the carbon is not wetted well by the cast iron. This gap is partially filled during operation due to expansion of the stub and the cast iron at high temperature.

Depending on the cast iron thickness, composition and casting conditions, the shrinkage of the cast iron is greater in the upper portion of the interface than the lower one. In operation, the contact is initiated at the lower part of the interface since the residual gap is smaller and the temperature is higher. Consequently, the non-uniformity of the gap at the interface as well as the variable radial expansion of the metal portion result in a partial contact at the cast iron to carbon interface. Since the shrinkage is dependent on the cooling rate, it is difficult to fully control the resulting residual gap. Also, almost no current flows through the circular bottom of the stub due to lack of contact pressure [3]. These factors lead to an additional electrical resistance, thus a higher production cost.

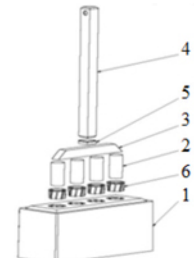


Figure 1. Anode assembly [2]

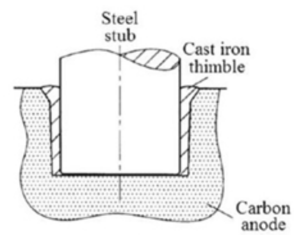


Figure 2. Anode connection [3]

The objective of the project is to develop a new anode assembly design in order to minimize the cost related energy loss and rodding operations. The development of a new design includes the following four steps:

- Conceptual study;
- Interrelation of key parameters;
- Proposal of a new design;
- Evaluation of the electrical performance.

Previous work
Stub to carbon resistance
In 1976, using *in situ* measurements, Peterson [1] has estimated that 7% of the total voltage drop is due to the anode assembly, out of which 25% is attributed to the stub to carbon (STC) connections. It concludes shortly after that the cast iron thickness between the stub and the carbon has a direct impact on the STC resistance.

In 1984, Brooks and Bullough [4] demonstrated that the electrical contact resistance (ECR) is a function of temperature and contact pressure. This dependence is then quantified in 1985 for a carbon/steel interface by Rhedey and Castonguay [5]. Figure 3 shows a representation of the original results done by Molenaar *et al.* [2] demonstrating three distinctive regions of the contact resistance variation.

Geometry modifications
In the eighties, Brooks and Bullough [4] and Peterson [6] have suggested design chart for cylindrical connectors. They propose different cast iron thickness for selected stub diameter to optimize the contact pressure without cracking the anode.

In 2001, the results of Richard *et al.* [7] showed that adding more flutes or increasing their length to maximize the nominal contact surface can increase the voltage drop compare to the original design.

In 2007, Wilkening and Côté [3] used a small bench-scale set-up to measure the STC resistance isothermally to conclude that:

- in the lower temperature range up to about 600°C, the ECR increase with thickness of the cast iron sleeves due to the higher shrinkage of the thicker cast iron layers;
- the contraction of steel and cast iron at the α to γ phase transition increase the ECR (see Figure 4 and 5).

In 2009, Richard *et al* [8] developed a coupled thermal-electrical-mechanical (TEM) model which led to the same conclusion regarding the addition of flutes. These results show that, in some cases, the voltage drop increases even with a higher nominal contact surface. Therefore, the real contact areas (via contact pressure) and their location has to be taken into account when determining the electrical performance.

In the same year, Li *et al.* [9] used a thermo electric (TE) model to study the impact of increasing the stub diameter and the number of stub of an industrial scale anode assuming a constant ECR on the cast iron/carbon interfaces. They concluded that these two elements decrease significantly the voltage drop by maximizing the contact area and improving the uniformity of the current distribution in the anode. However, greater number of stubs requires a longer crossbar, consequently, the thermal expansion of the longer crossbar and the larger diameter of stub increase the stress in the carbon bloc. This might result in anode cracking during operation. The increased frequency of anode cracking adds additional operational problems as well as manual work requirement.

In the same year, Fortin *et al.* [10] built a fully coupled TEM model showing that the crossbar dilatation generates significant stress on the outer stub hole (thus uneven contact pressure), therefore, creates a toe-in effect of the crossbar. This element leads to a premature maintenance of the anode assembly.

In 2013, Molenaar *et al.* [11] used a high amperage testing facility to study the impact of deterioration parameters including the change of stub diameter, height and the eccentricity of the stub in the stub hole on anode performance. He concludes that a net penalty of more than 50 mV is possible for a deteriorated anode rod fleet.

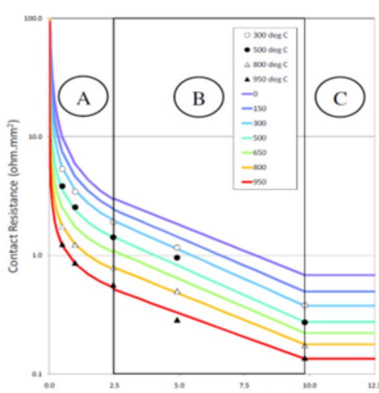


Figure 3. Chart of contact resistance relationships with overlay of original data [2]

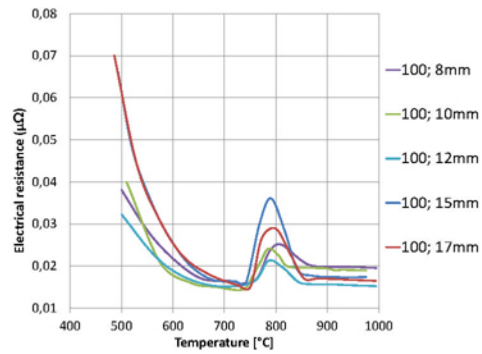


Figure 4. Effect of cast iron thickness in the range of α-γ phase transition on the STC resistance, from [3]

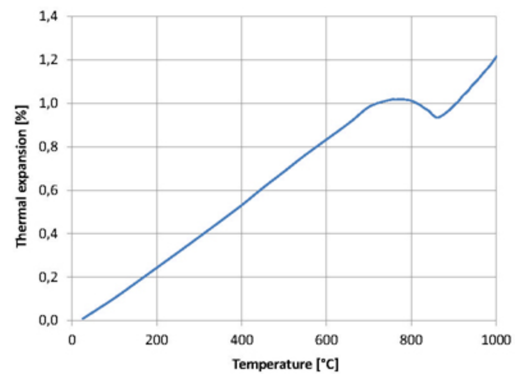


Figure 5. Thermal expansion of new mild steel, from [3]

Patents

In 1986, Friedli *et al.* [12] proposed to attach the carbon block to the studs using an adhesive mass which is mechanically strong and a good electrical conductor. The studs would be inserted in the cold-poured adhesive and vibrated until they come to rest on the bottom of the anode holes. This approach allows connexion to the carbon block without using cast iron, thus, possibly provides a better contact between the studs independent of the geometry (at least after insertion). Considering the relation shown in Figure 3, it is possible that the adhesive mass does not allow an effective contact pressure buildup during operation due to its low stiffness.

In 2002, Tsomaev [13] proposed to slide a large rectangular head of metal into a preformed slot in the carbon block (see Figure 6). This approach would improve the mechanical and electrical contact with increasing the contact area between the head and the carbon block and eliminating the need for cast iron. The approach allows possibly a more uniform current distribution in the anode and a better control of the ECR because of the absence of residual gap and the free expansion of the head in his longitudinal direction. But it is possible that, after repeated anode cycles, the geometrical changes induced in the head due to extreme conditions of the process will possibly mismatch the preformed slot of the carbon leading to an increasing ECR.

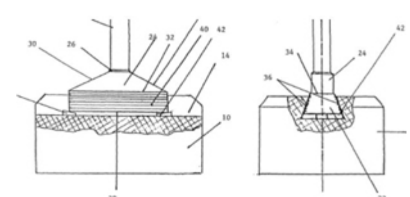


Figure 6. Anode assembly proposed by Tsomaev [13]

In 2012, Fafard *et al.* [14] proposed to connect the carbon block to a longitudinal bar using a pourable conductive material such as cast iron (see Figure 7). This approach would allow a reduction in energy loss due to a larger contact surface and a better distribution of the current in the anode. However, being not able to precisely control the cooling rate of the pouring material during sealing, there is possibilities that the non-uniform gap at the cast iron/carbon interface after solidification will decrease the real contact area.

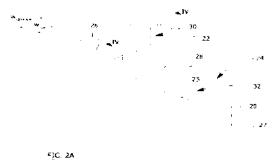


Figure 7. Anode assembly proposed by Fafard *et al.* [14]

Conceptual study

To propose an optimal design, it is essential to identify the key parameters from the previous work which lead to an improvement of the electrical performance and the reduction of the cost related rodding operations.

Resistance at the connector/carbon interface

The resistance at the connector/carbon interface is dependant of:

- the ECR;
- the nominal contact surface for a given ECR;
- the distribution of the real contact area at the interface;

Figure 3 shows that, for a given temperature, the minimum ECR is achieved with a contact pressure of 10 Mpa. However, it is known that an excessive contact pressure might create a significant stress in the carbon block leading to anode cracking. Finally, another crucial element is to maximize the nominal contact surface.

Since the operational temperatures in the anode connection zone is between 550°C and 950° [3], the ideal situation would be to obtain a minimum ECR (corresponding to 10 Mpa and more) on the entire nominal contact surface at 550°C and maintain this electrical performance up to 950°C. Thus, the thermal expansion of the connector should be minimized after 550°C in order to avoid damaging the carbon block. However, to obtain significant contact pressures at 550°C on the entire nominal contact surface with a low thermal expansion of the connector, the gap at the connector/carbon interface must be minimal and uniform before the operation of the anode assembly.

Resistance of the carbon block

Li *et al.* [9] showed that a significant reduction of the resistance can be reached by increasing the number of stubs which leads to the improvement of the current distribution in the anode. This means that uniform current distribution at the top surface of the anode would allow the current to travel along a vertical path directly to the base of the carbon block (thus a shorter path) leading to a lower resistance.

Resistance of the crossbar

This is mostly affected by the cross sectional area of the crossbar (cutting plane perpendicular to current lines) and the material resistivity itself. Evidently, the cross section area of the crossbar has to be maximized and also be able to uniformly distribute the current to the stubs and connectors.

Maintenance and rodding operations

Decreasing the number of parts and simplifying their geometries might decrease significantly the cost of the maintenance and the rodding operations of the anode assembly.

Interrelation of key parameters

A conceptual study has identified the key parameters, factors affecting them and the elements that can be adjusted to optimize these key parameters. Figure 8 presents a diagram of the interrelation of the key parameters which are taken into consideration for developing the new anode assembly. The red boxes indicate TEM key parameters whereas the green boxes give TE key parameters.

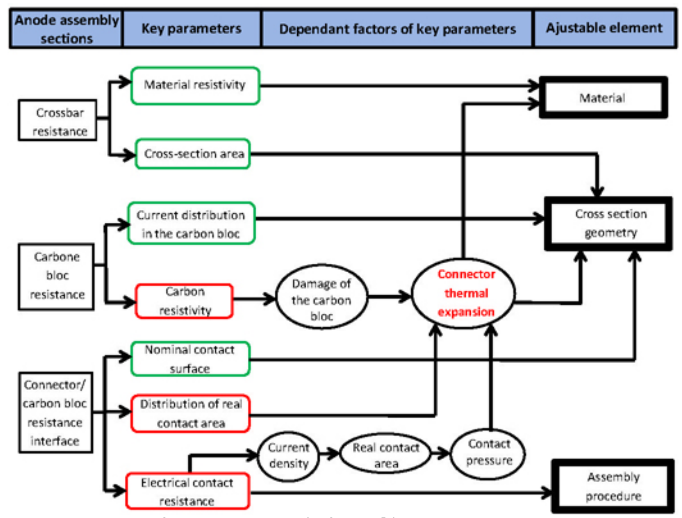


Figure 8. Interrelation of key parameters

It is also essential to consider the economic aspects related to the manufacture, operation, maintenance (degradation) and cleaning of the assembly.

Development of the new anode assembly

The next step is to determine, using Figure 8, the adjustable elements that optimize the key parameters via their dependant factors considering the industry practices.

As shown in Figure 9, the proposed approach is to introduce multiple thin rectangular steel connection elements into the carbon paste during the forming step of the anode. After baking, cast iron is poured between the modified crossbar and connection elements to allow the current to travel from the crossbar to the connection elements and also to support the anode via a preformed groove (not shown in Figure 9). In this configuration, the side surfaces of the connection elements distribute the current to the anode block.

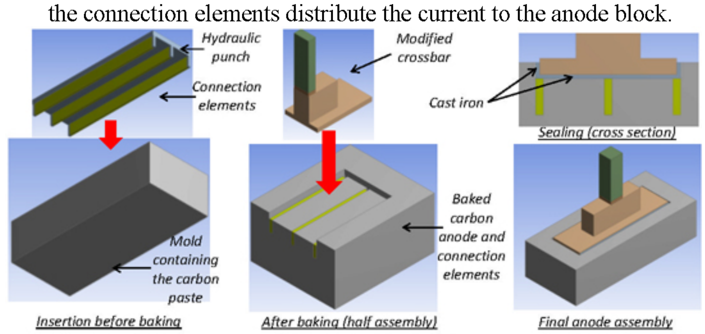


Figure 9. Assembly procedure of the new concept

Assumptions concerning the TE key parameters
The larger nominal contact surface and the more uniform current distribution of the new concept would significantly reduce the resistance of the anode assembly compared to the actual design.

Assumptions concerning the TEM key parameters
The proposed procedure of assembly is based on the fact that the densification of the anode during the baking process leads to possibly a larger contraction than the one caused by the cooling of the steel connection elements after the baking process. Also, the low expansion of the thin connection elements proposed in the new design would not cause any damage to the carbon anode during the baking process. Finally, considering the two previous assumptions, the approach would allow a low ECR for a range of thicknesses of the connection elements (the initial gap before baking being independent of the geometry). This would result in a robust electrical performance through the anode cycles.

Industrial practice advantages and disadvantages
Advantages of the new design can be listed as follows:

- cleaning the bath is easier considering the simpler geometry;
- maintenance of the modified crossbar is less costly considering the three welds between the stubs and the crossbar of the actual design (thereby greater lifetime);
- imposing gaps at strategic localisations at the carbon interfaces allows the modified crossbar and the connection elements to expand freely avoiding important stress in the anode/crossbar/connection elements without penalizing significantly the electrical performance;
- reduce the non-consumed part of the anode;
- can result in a more uniform carbon density around the anode connection.

On the other hand, some disadvantages are also identified such as:

- makes the forming operation of the anode more complex;
- requires an important modification in the rodding processes;
- can cause a premature carbonization of the connection elements;
- requires more steel and therefore heavier.

Evaluation of the electrical performance

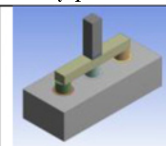
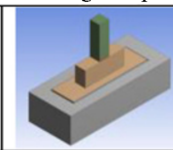
The potential of the new concept is evaluated using two different methods. Firstly, the TE key parameters are estimated using a true scale representation of the new and the actual design in a TE model. Secondly, the TEM key parameters are evaluated using laboratory tests simulating the baking as well as the operation of small-scale assembly.

Evaluation of the TE key parameters

As shown in Table 1, the true scale representations of both designs allow, on a comparative basis, the estimation of the possible electrical gain due specifically to modification of the TE key parameters assuming:

- the ECR is constant on the entire nominal contact surfaces;
- for the actual design, the nominal contact surfaces correspond only to the circumferential contact of the three thimbles;
- for the new design, the nominal contact surfaces correspond only to the side surfaces of the three connector elements;
- all the other surfaces in contact with the carbon are insulated;
- the same boundary conditions have been prescribed;
- only the geometry between the clad and the bottom of the stub hole (130 mm deep) has been modified.

Table 1. Impact of TE key parameters on voltage drop

		
Nominal contact surface[mm^2]	355 000	615 600
Carbon mass in butt [kg] (150 mm height)	221	206
Cast iron mass [kg]	33	34
Steel mass [kg]	313	349
Voltage drop: Clad to anode base [mV]	**291**	**230**

Considering the presented assumptions in the TE model, a fictitious gain of 61 mV is obtained by improving principally the nominal contact surface and the current distribution.

Evaluation of the TEM key parameters

The assumptions made previously will be confirmed by evaluating the interface electrical performance which depends on the following TEM key parameters:

- Electrical contact resistance;
- Increase of the carbon resistivity due to cracking;
- Distribution of real contact area.

To quantify and analyse the TEM key parameters, laboratory tests are used. First, to simulate the baking process with the new concept, the green anode samples including the inserted steel connection element are baked in a furnace using the industrial heating rate. Once baked, a small-scale set-up using a current source of 4A and a furnace is used to provide the voltage drop between the steel connection element and the carbon in an isotherm environment. By selecting the right performance indicators, it is possible to evaluate the TEM key parameters.

Performance indicators
The experimental results of Wilkening and Côté [3] at isothermal condition (Figure 4) show that the electrical performance is highly correlated with the thermal expansion of steel (Figure 5). Since the thermal expansion is related to the generation of the contact pressures and these are related to the ECR (Figure 3), this correlation allows us to identify several elements as performance indicators to evaluate the STC resistance using experimental results.

Figure 4 shows that there is an asymptotic trend at a lower temperature when the cast iron thickness is smaller. This trend suggests that the contact pressures are optimal (region 'C' of Figure 3) since the additional thermal expansion of the metal portion does not reduce the STC resistance. This indicates that, after generation of significant contact pressures, the carbon can support an additional expansion of the metal portion without considerable impact on the electrical performance. This interpretation is also supported by the fact that the three configurations showing an asymptotic trend at a lower temperature (100/8, 100/10 and 100/12) show a smaller variation in their resistance at the α to γ phase transition (causing a contraction) compared to two other configurations (100/15 and 100/17). Thus, according to Figure 3, a decrease of the contact pressures initially located in region C has a lower impact on the ECR than if these pressures were initially in region B.

Considering the strong correlations between the variation of the thermal expansion of steel (Figure 5) and the voltage drop tendencies, the evaluation of the TEM key parameters of the steel connector/carbon interface is then performed by the following performance indicators:

1) a smaller voltage drop is obtained between the steel connection element and the carbon;
2) a smaller increase in voltage drop at the α to γ phase transition of steel suggest higher contact pressures at 750°C at the steel connector element/carbon interface:
3) an asymptotic tendency of the voltage drop before 750°C suggest an ECR close to the minimum;
4) a higher voltage drop at lower temperature suggest a larger residual gap.

Considering the same correlation, it is possible to link a damaged carbon block by the following indicators:

5) an increase in the voltage drop before the α to γ phase transition of steel;
6) a decrease in voltage drop during the α to γ phase transition of steel.

Finally, measurements and microscopic observations after baking of the steel connector/carbon interface for different connector thicknesses can lead to a better understanding of the experimental results.

Bench-scale measurements

Since the approach uses a steel/carbon interface to distribute the current, the experiment consists of recording a voltage drop between the steel connector and the carbon sample (see Figure 10) to evaluate the three TEM key parameters using the performance indicators.

Besides the voltage drop, the resistance between two monitored points depends also on the amperage. However, the current density is very difficult to obtain considering his variability due to:

- the significant heterogeneity of carbon and thus its properties;
- the current input and output cannot be applied perfectly on the whole surface;
- the current distribution in the carbon changes with the connector geometry and the real contact area localisation;
- the current flow shifts across the connector/carbon interface during heating [11,15].

Since the current input is known, the adopted strategy is to locate a measurement plane in the carbon where the variation of the current density is minimal. As shown in Figure 10, by covering uniformly this plane with measured points (P1, P2, P3, …), the average resulting voltage drop between the reference probe on the connector and the probes in the carbon block (Pref-P1, Pref-P2, Pref-P3, …) gives a more reliable data minimising the impact of the current density variation. A representation of the assembly in a TE model provides an efficient way to locate this measurement plane (see Figure 10).

To extract only the TEM key parameters, all other factors affecting the voltage drop must be considered (green boxes in Figure 8). To do so, each tested sample has been represented in a TE model according to their geometry (carbon block, connector, connector hole), location of the measurement probes and TE properties. This way, it was possible to obtain the measured experimental voltage drop at a specific temperature for a prescribed ECR. Then, the prescribed ECR from the TE model (called ECR_Num) depends only on the TEM key parameters. ECR_Num will be used as a more reliable evaluation quantity in replacement of the voltage drop by removing the variations cause by the TE key parameters. Note that the performance indicators based on tendencies stay the same with the ECR_Num.

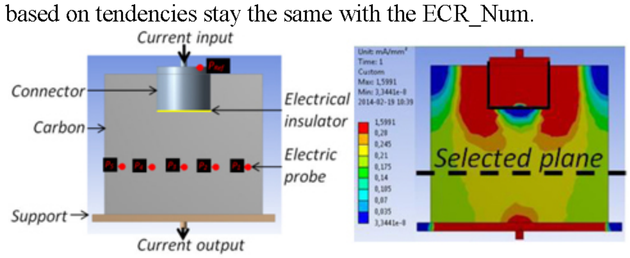


Figure 10. Numerical representation of the small-scale setup and the variation of current density in the assembly

Results and discussion

Experimental validation

Before testing the TEM performance parameters, simple configurations where a steel cylinder is placed in a baked carbon stub hole with different residual gaps were tested to make sure that the experimental measurements followed the performance indicators.

*Nomenclature:
<Geometry>_< Diameter or thickness [mm]>_<Initial Gap>_<Baked or not>
+: means a larger gap at the insertion;
- : means larger initial contact pressure at the insertion.

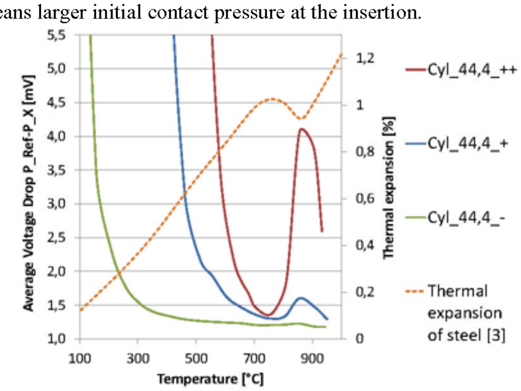


Figure 11. Impact of initial gap

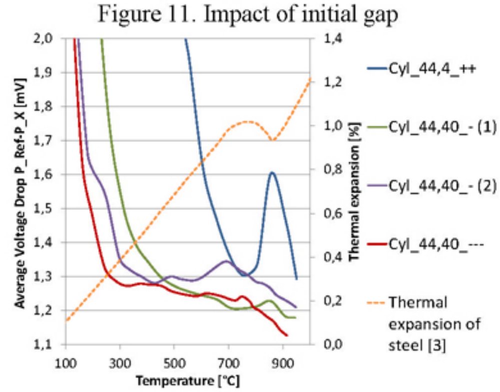


Figure 12. Impact of cracked carbon

Figure 11 demonstrates that the experiment procedure is accurate enough to be able to use the performance indicators with the voltage drop and the ECR_Num, the latter showing the same trends.

Figure 12 shows the impact due to carbon cracking on the voltage drop by testing samples with high initial contact pressure. The sample of Cyl_44,4_- (1,2) and Cyl_44,4_--- showed major cracks after the operational test. The results demonstrate that the cracking of the carbon block can increase the voltage drop before the contraction of the steel. Also, the damaged carbon does not increase significantly the voltage drop for a small dilatation and the contraction of the steel at the phase change can decrease the voltage drop. Finally, electric probes from the same plane of cracked carbon samples show high variations for small connector dilatations (hence small temperature change) suggesting abrupt changes in current line directions cause by carbon cracking.

Thickness evaluation with baked assemblies

Figure 13 shows the effect of connector thickness that has been baked on the ECR_Num. The results suggest that a thinner connector seems to be beneficial since ECR_Num was low at the beginning of operational temperature and the small dilatation afterwards kept the ECR_Num low. Also, the results of the samples Prism_6,35_Baked suggest that carbon anode might be cracked due to the increase before the phase change and the decrease of ECR_Num during the phase change of steel. Higher instability between electric probes as been also observed from Prism_6,35_Baked. At room temperature, for similar initial gap, thicker is the connector, lower the initial contact pressure will be and higher the phase change increase will be. Observations also show that the samples with the thickness of 12,7 mm and 6,35 mm are practically joined to the carbon block and can't be extracted easily from the slot after the baking process at room temperature.

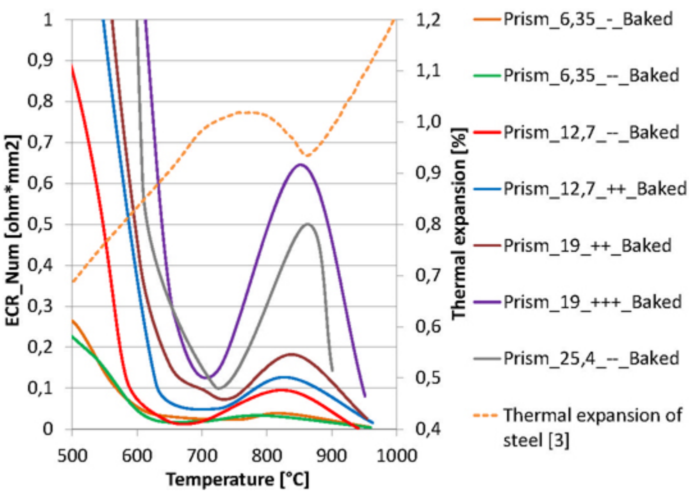


Figure 13. Impact of thickness connector

Considering the variation in the initial gap and the thermal, mechanical and electrical properties, it is important to mention that more tests are necessary to validate the results.

Conclusions

For a same ECR on the entire connector/carbon interface, the new design gives significantly lower voltage drop compared to the conventional design by improving principally the nominal contact surface and the current distribution.

Also, the experimental results show that the baking process of a connector/carbon assembly can reduce the residual gap at the interface and even generate initial contact pressures.

Finally, a low ECR can be achieved with the new approach for a certain range of thickness considering the corresponding performance indicators.

Future work

- Verify the repeatability of the experiments;
- Observations and measurements of the tested samples;
- Determine the evolution of the electrical performance with respect to the aging of the insertion elements considering its reuse in the anode assembly;
- Determine the suitable geometry of the mechanical support and the location of the outer insertion elements;
- Optimize the design considering an economic study;
- Determine the electrical performance of the final prototype in comparison to the actual anode assembly design taking into account the TEM behavior.

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