Storvik high conductivity anode yoke with copper core

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Abstract

Copper is already used in aluminium electrolysis cells as inserts in steel cathode collector bars with the aim of lowering cathode voltage drop. With the same idea in mind, Storvik has designed and manufactured cast steel-copper core anode yokes. Storvik together with partners has developed a method of combining copper and steel through casting. This method is quite different to the conventional methods used in the aluminium industry today (gun drilling and heating) which is not possible for anode yokes. In this paper, the results of mathematical modelling and laboratory experiment, using cast steel-copper core anode yokes are presented. The modelling showed 43 % voltage drop reduction in the copper core yoke in comparison with standard steel yoke. Laboratory tests shows 29 % voltage drop reduction even though the specimen had casting defects. The casting method achieved 100 % molecular bonding of metals with iron particles penetrating several mm into the copper and copper particles penetrating 20 µm into the iron at the interface between the two metals. Storvik is now preparing a full scale industrial trial in a smelter. Economical analysis of the gains by using copper core yokes will also be presented in the paper.

Keywords: Copper core anode yoke; copper-steel casting bond; anode yoke voltage drop; voltage drop; high conductivity.

1. Introduction

The aluminium industry has a need for good heat and electrical conductors that are resistant towards corrosive environments. Metals such as copper (Cu) and aluminium (Al) are preferred conductors were copper shows the best properties. Cu is more expensive than aluminium and the Cu density is higher than that of Al. Al is frequently used rather than copper because it is lighter for the similar electrical conductance. Steel is used in areas which are exposed to high temperatures. Steel also has very good mechanical properties, however the electrical conductivity is relatively poor compared with Cu and Al. Table 1 gives the resistivity and density of aluminium, copper and iron.

Table 1. Resistivity of aluminium, copper and steel at 150 °C.

Material	Resistivity (µΩm)	Density (kg/m^3)
Aluminium busbars	0.04314	2 700
Copper	0.02647	8 960
Iron	0.231	7 874

In aluminium industry, the focus is particularly aiming at anodes and cathodes. Those are used in an environment where steel and cast iron are common but very poor conductors in comparison to aluminium and copper. However, they are the best materials due to their resistance to high temperature and mechanical strength. To decrease electrical resistance, copper and aluminium are used in combination with steel and cast iron. Aluminium and is used for anode rods, which are the least exposed to high temperature. Copper is sometimes mechanically inserted in steel cathode collector bars. There are many published articles about new cathode technology referring to usage of copper and steel as combined conductors, this technology increases the pot efficiency and the refractory lining lifetime considerably, due to the fact that the current distribution is more even with copper inserts [1]. This is mentioned as a reference to our invention as the theoretical analysis shows that the current distribution is more equally distributed through the cell with copper core in the steel. Copper can also be done in anode yoke as described in this paper. Basically, Storvik's main target with the new Storvik High Conductivity Anode Yoke is reduced voltage drop in the anode yoke.

2. About Storvik AS

Storvik roots goes back to 1913 and started by the local black smith Nils Storvik. Figure 1 shows the old smithy at Viklandet, Sunndalsoera. The company Storvik as an industrial company was founded in 1952 upon the construction of the Hydro Aluminium smelter in Sunndalsoera (then belonging to Årdal og Sunndal verk). First metal (aluminium) was poured in 1954. Storvik is now a company with the head quarter located in Sunndalsoera, close to Hydro Aluminium Sunndal. In addition to the main office, we have branch offices in the Czech Republic, Iceland, Russia and Kristiansund, Norway. Storvik employs a total of 85 persons. Storvik provides multidisciplinary services, products and projects to Norwegian and international primary and secondary aluminium industry, which is the main market. Storvik, also delivers projects and products to oil and gas industry and hydro power stations.

Figure 1. The old Storvik smithy at Viklandet, Sunndalsoera.

3. The pilot project - "Storvik High Conductivity Anode Yoke"

During 2014 and 2015, Storvik has performed a pilot project of the Storvik High Conductivity Anode Yoke. The pilot project has been funded by Innovasjon Norge. This paper will basically describe the pilot project including findings and possible next steps for the invention.

The basis for this study has been to verify the following parameters:

1. New design anode yoke for pilot project,

2. FEM analysis of voltage drop,
3. Bonding of metals (Cu and Fe),
4. Mechanical test of bonding of metals,
5. Small scale testing of voltage drop in laboratory,
6. Casting of prototype anode yoke,
7. Apply for patent.

4. Design

A new design for a cast anode yoke was made by Storvik with the aim not to conflict our customers design and IP. The new yoke was designed as a 2 stud version with regular cast steel, typically GS 45 material quality (reference design) and one version with cast steel GS 45 including a 50 mm diameter Cu core (Storvik High Conductivity Anode Yoke) as shown in Figure 2. These designs will be used for calculations/simulations, prototype casting and voltage drop measurements in the laboratory. For a full scale industrial trial Storvik will use an existing design provided by customer.

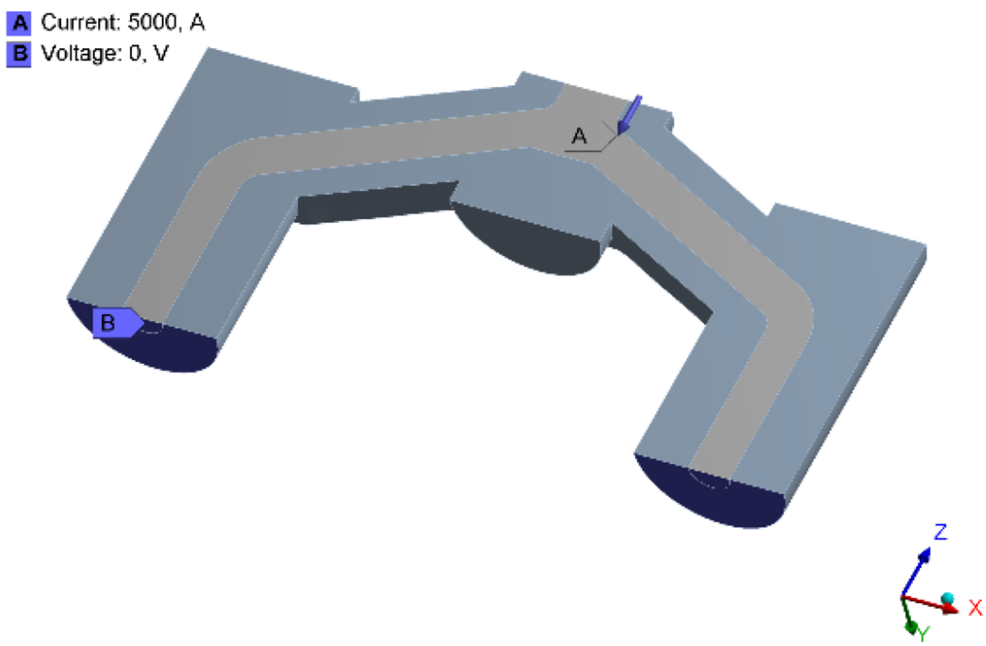

Figure 2. The new design copper-steel cast anode yoke with boundary conditions for FEM model.

5. FEM analysis

A DC conduction analysis for the Storvik High Conductivity Anode Yoke structure was evaluated by using of Finite Element Method (FEM) analysis. The objective of the analyses is to find the current density distribution and the resistance of the cast anode yoke when 10 kA (5 kA each stub) current is applied on the structure. Case A and case B with the steel-copper and the structural steel are modeled, respectively.

A mesh consisting of 3D hexahedron dominant and tetrahedron elements are used. The element mesh is illustrated in Figure 3a. The model consisted of 24 318 solid elements and

94 241 nodes. The maximum element size is set to 10 mm. Symmetry condition is used in the model. The current distribution in the yoke is shown in Figure 3b. The calculated voltage drops and resistances are summarized in Table 2.

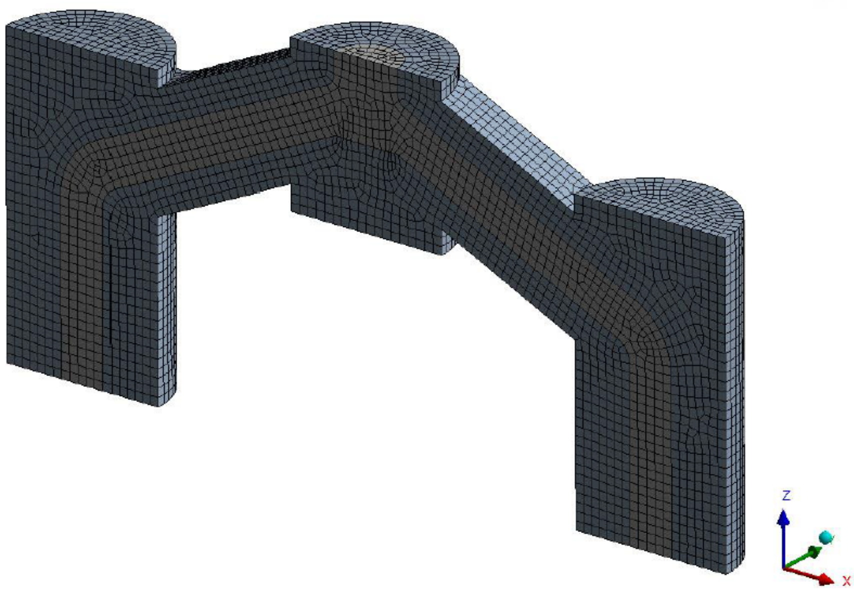

Figure 3a. The finite element mesh in the model.

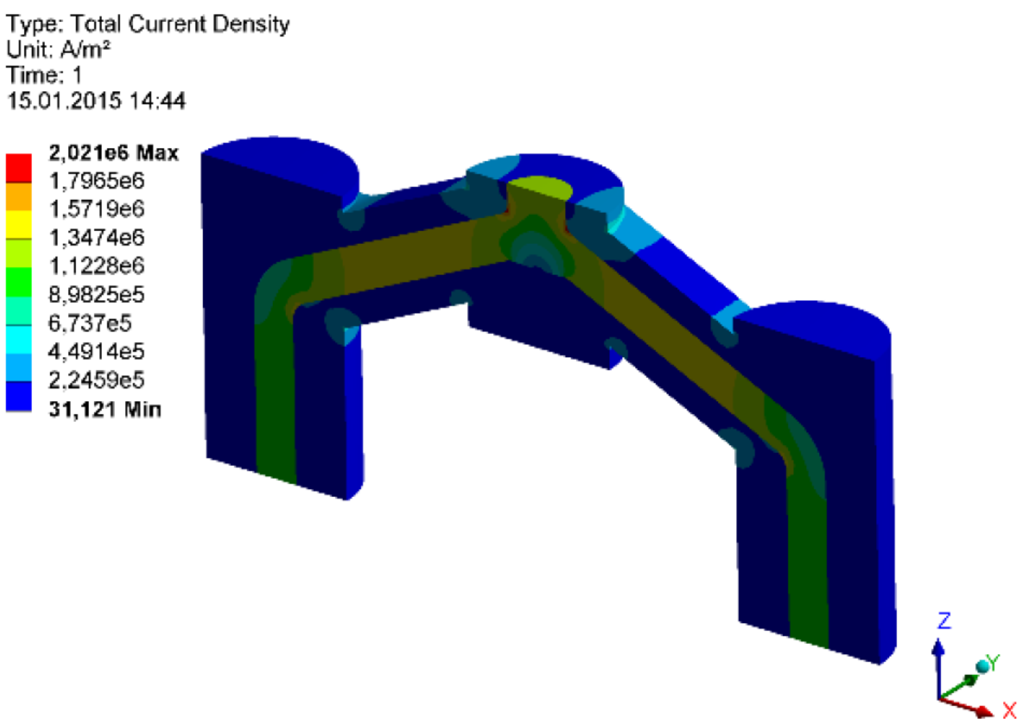

Figure 3b. Calculated current densities in the yoke.

Table 2. Anode yoke voltage drop and resistance for case A and case B .

Case	Material	Applied current (kA)	Voltage drop (mV)	Resistance (μΩ)
A	Steel-copper	5	16.4	3.28
B	Steel	5	29.0	5.8

By embedding a cast copper into the steel anode yoke the resistance is reduced by approximately 43 % in the example calculated.

6. Metallographic investigation of bonding between copper and steel

Elkem Laboratory in Kristiansand, Norway [2], have been investigating the bonding of metals. A combined material consisting of Cu and Fe has been investigated with respect to the properties at and close to the interphase between the two metals. The connection between the metals seems to be without any crack or pores but some porosity is found elsewhere in the material both in the Cu and in the Fe. The micrographs show that some Cu has diffused into the steel but even more Fe seems to have been dissolved into the Cu. In the Cu there is a lot of Fe containing particles of two different sizes, 20 μm and 1 μm. The Fe- particles in the Cu reach several mm into the metal. The Cu is dissolved into the Fe and reaches around 20 μm from the interphase. A specimen was cut from the received Cu/Fe sample and polished down to 3 μm, see Figure 4, Lower grey part is steel and upper part is copper. In the marked ring Figure 3 we can observe a Fe rich area dissolved in to the Cu.

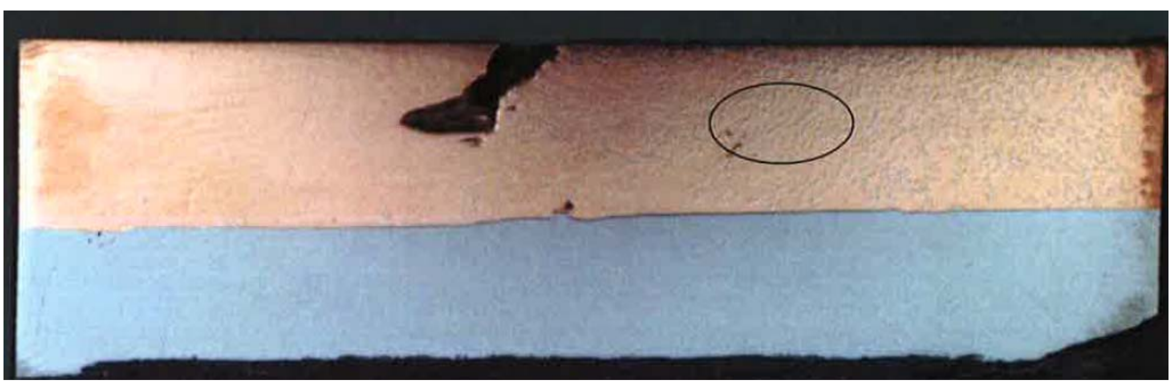

Figure 4. Specimen of Cu/Fe joint.

By doing a 200 μm scan over the interface, we can see the depth of the Cu diffusion into the Fe-side. The chemical analyses have been performed along the yellow line and the level of Fe, Cu and Si is given in the graphs in Figure 5 below.

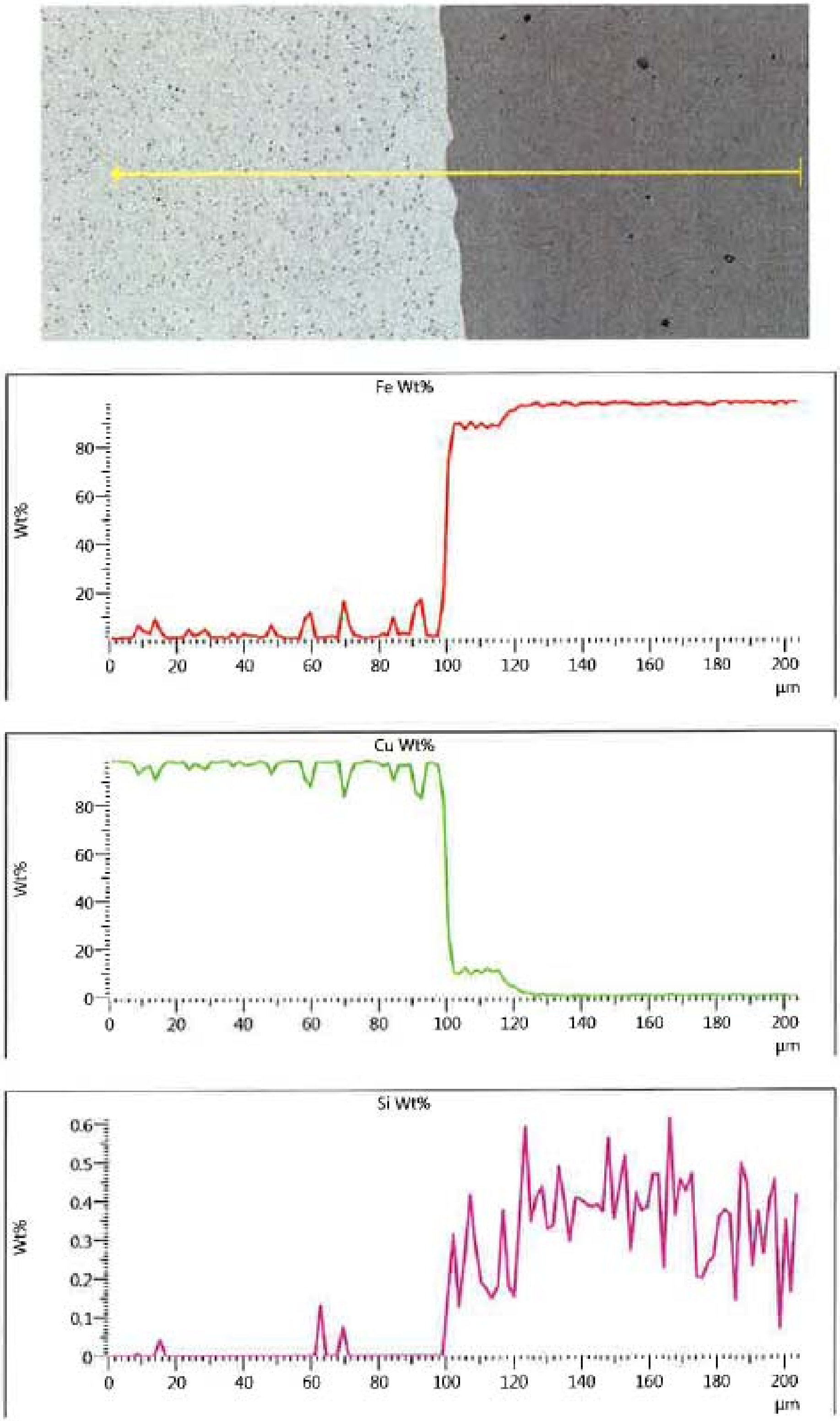

Figure 5. 200 µm scan over the interface.

7. Destructive testing of mechanical bonding of Cu/Fe

Destructive testing was performed by a hydraulic press for one specimen to mechanically test and visually inspect the connection/bonding of the Cu and Fe. Results is that connection of metals are 100 % molecular, see Figure 6 (picture taken from video of the destructive testing). Figure 7 shows a detailed cross-section of a stub.

A destructive test was also performed on the full scale Storvik High Conductivity Anode Yoke to inspect the steel and copper casting. Destructive testing shows minor casting defects in the Cu core, which is solvable by making smaller changes in the casting technology. Several more samples would now be cast to verify that it is possible to cast the Storvik High Conductivity Anode Yoke free of casting defects and make sure that the product is ready for implementing into a full scale industrial trial in the potroom. It would also be necessary to perform lab scale test to verify the voltage drop of a full scale anode yoke with Cu core.

8. Lab scale tests voltage drop

8.1. Prototype casting

Throughout the project period several small-scale samples (studs) have been cast, see Figure 6. One of the challenges occurred was the difference in melting temperature and shrinkage during solidification which have been a challenge for the casting process. However as seen on Figure 6 this have been solved properly and the casting is almost free of defects.

The prototype casting was made and is shown in Figures 8 and 9. The visual inspection of the full scale Storvik High Conductivity Anode Yoke Figure 8 shows that surfaces quality are acceptable and free of casting defects.

Figure 6. Destructive testing of molecular bond.

Figure 7. Small scale specimen of stubs.

Figure 8. Storvik HC Anode yoke with Cu core.

Figure 9. Machined cross section of anode yoke.

8.2. Full scale trial

Storvik are in discussions with aluminium producers about performing a full scale trial, however, no test site has been agreed yet. At this stage the focus has been to verify and perform small scale testing. The full scale testing will be performed with oxygen free Cu for better conductivity, all small scale tests and specimens have been made using Cu with oxygen.

9. Economical gains

All calculation on savings is theoretical and is based on a yoke with a length on 280 mm; savings will increase with the length on the yoke.

Storvik High Conductivity Anode Yoke can be adapted to fit any primary aluminium smelter using prebake anode technology. Experiments can be made in order to optimise designs, e.g., with respect to the length of Cu core. Storvik has made calculations to show possible savings by embedding cast Cu core in the steel anode yoke. The results are shown in Table 2. For a 300 000-tonne aluminium prebake smelter with 360 cells, the energy cost savings will be approximately 477 000 US $, assuming energy price of 40 $/MWh and anode voltage drop reduction of 12.6 mV as per Table 2. This has to be balanced against the increase of capital cost for yokes with copper core.

Table 3. Estimated savings due to reduced voltage drop in anode yoke with copper core, US $.

Parameter	Unit	Value
Smelter capacity	kt/year	300
Number of pots		362
Number of anodes per pot		30
Amperage	kA	300
Current per anode	kA	10
Anode yoke voltage drop without Cu	mV	29
Anode yoke voltage drop with Cu core	mV	16.4
Voltage reduction	mV	12.6
Energy saving per potline per year	MWh/year	11920.6
Price of energy	$/MWh	40
Operating cost saving per potline	$/year	476824

10. Patent

Storvik applied for a patent on 31 December 2014. The application "20141570" is pending at Patentstyret in Norway.

11. Acknowledgement

Storvik received funding from Innovasjon Norge for the pilot project.

12. References

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