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DEVELOPMENT AND APPLICATION OF AN ANSYS® BASED THERMO-ELECTRO-MECHANICAL ANODE STUB HOLE DESIGN TOOL

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Abstract

At the 2009 TMS conference, we could observe a renewed interest for the optimization of anode stub hole design. This is not surprising considering that 50 mV is costing about 1 MM$ per year to a typical modern prebaked anode smelter producing around 220,000 T per year according to Richard [1] and that we can estimate that the contact resistance voltage drop at the cast iron/anode carbon interface is about 60 mV (assuming 0.1 m^2 of contact surface per stub hole, 3000 A of current per stub and 2 micro-ohm m^2 of the average contact resistance) which translate to 1.2 MM$ per year of operational cost for a typical modern smelter for that cast iron/anode carbon contact resistance alone.

Considering the above, it is easy to understand that there is a good incentive to optimize the stub hole design in order to minimize the cast iron/anode carbon contact resistance voltage drop. For that reason, the author took advantage of the recent development of ANSYS® contact elements library to develop an ANSYS® version 12.0 based fully coupled TEM anode stub hole design tool that is now available to the whole aluminium industry through GeniSim Inc.

Historical background

The typical approach for the last 20 years has been to optimize the stub hole using 3D thermo-electric (TE) mathematical modeling tools [2,3]. The weakness of this approach is that the contact resistance has to be considered as constant and the value of that constant as to be defined as a model input. As a result, the model is only sensitive to the cast iron/anode carbon contact interface surface area leading designers to increase that interface surface area (see per example figure 2 of [3]) disregarding completely the mechanical impact of those stub hole design changes.

This approach can be very misleading because the value of the contact resistance that has to be assumed constant in TE models, is in reality strongly dependant of the applied pressure at the contact interface as initially reported in [4,5], and again at the 2009 TMS conference in [6]. Furthermore Richard [1], conveniently fitted the raw data into a 12 parameters equation that is function of both pressure and temperature.

The geometry of the stub hole is such that the cast iron/anode carbon interface contact pressure is function of the local temperature in that region that is itself function of the local Joule heating that is itself function of the contact resistance that is itself function of the contact pressure.

Because of that cycle dependency, only a fully coupled thermo-electro-mechanical (TEM) modeling tool can be reliably used as a stub hole design tool because only this type of model is able to fully reproduce the full complexity of the contact resistance physical behavior.

Richard [1] was the first to develop an ANSYS® based TEM anode stub hole model and to use such a model to do some stub hole design optimization work. Unfortunately, the ANSYS® version available at the time was not supporting thermo-electro-mechanical contact elements preventing the development of a fully coupled model. For that reason, the model he developed was only weakly coupled. Furthermore, the ANSYS® version available at the time was not even supporting thermo-electrical contact elements forcing the usage of "clumsy" link elements to represent the thermo-electrical contact behavior which added a lot of complexity into the model development work.

Following Richard's initial effort, Goulet developed a fully coupled TEM model based on Laval University proprietary finite element code FESh++ [7,8,9]. FESh++ is a fantastic academic finite element code in advance of ANSYS® for the implementation of complex material behavior law elements so it is extremely useful to carry-up fundamental research work. Unfortunately, it is not the most practical tool to carry-up design optimization modeling work in the aluminium industry. For that, ANSYS® have been the code of choice of the industry for over 25 years now (see per example [10,11]).

ANSYS® version 12.0 based thermo-electro-mechanical anode stub hole model development

For that reason, the author took advantage of the recent development of ANSYS® contact elements library to develop an ANSYS® version 12.0 based fully coupled TEM anode stub hole design tool that is now available to the whole aluminium industry through GeniSim Inc. That model is based on the usage of ANSYS® SOLID226 3D thermo-electro-mechanical second order element together with CONTA174 and TARGE170 thermo-electro-mechanical contact pair elements. Furthermore, CONTA174 element supports the setup of a pressure and temperature TCC (thermal contact conductance) and ECC (electrical contact conductance) values through the %table% option.

Having all the required components to model the complex stub hole cast iron/anode carbon contact resistance complex physic in ANSYS® version 12.0, it was quite strait forward for the author to take advantage of the classic ANSYS® parametric design language (APDL) to develop some demonstration anode stub hole models and to used them as efficient stub hole design tools.

First demonstration model

The first demonstration anode stub hole model presented here is a quarter stub hole model that would represents the quarter of an anode for a 1 stub per anode block anode design, 1/8 of an anode for a 2 stubs per anode block anode design, 1/12 of an anode for a 3 stubs per anode block anode design etc. (see figure 1 for the full model mesh). In such a quarter stub model, it is easy to support stub hole design having 4, 8, 12, 16 standard inclined flutes. The first model presented here is using the 8 flutes option (see figure 2 for the cast iron only model mesh).

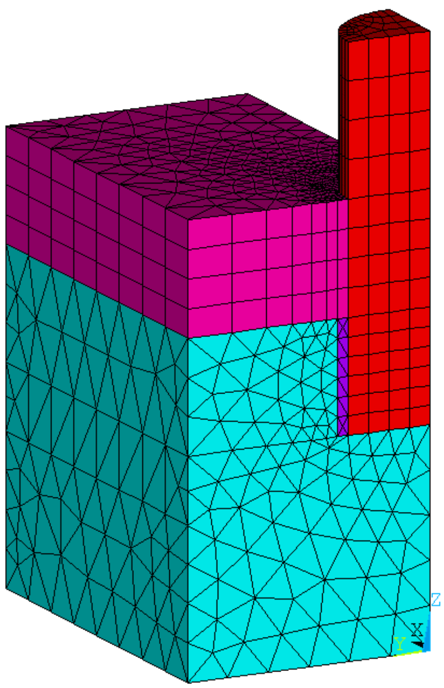


Figure 1: Quarter stub hole thermo-electro-mechanical model, full mesh

This defined the model topology leaving the option to model thousands of different actual anode stub hole geometries. Per example, it is possible to vary the stub diameter, the stub hole depth, the minimum cast iron thickness between flutes, and the flute dimensions: width at the base, width at the tip and depth.

For all the cases presented here, the stub diameter was kept to 18 cm and the stub hole depth was kept to 12 cm. For the first case presented, the minimum cast iron thickness was set to 12 mm, the flute width at the base was set to 18 mm, the flute width at the tip was set to 14 mm and the flute depth was set to 8 mm. This geometric setup gives an average of 14 mm of cast iron thickness between the stub and the anode carbon which, according to Brooks [12], is the main stub hole design criteria.

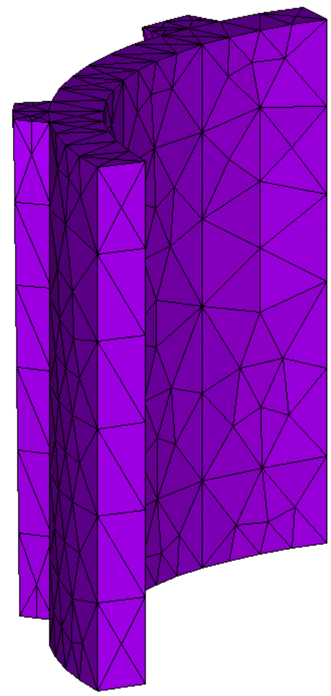


Figure 2: Quarter stub hole thermo-electro-mechanical model: cast iron mesh 8 flutes design

This geometric setup was analyzed two different ways, in the first model run, the “traditional” constant contact resistance setup was used, a typical value of 2 micro-ohm m^2 being selected for that constant value. The model prediction for that run is 286 mV for the total voltage drop from the top of the stub to the bottom face of the anode block (see figure 3).

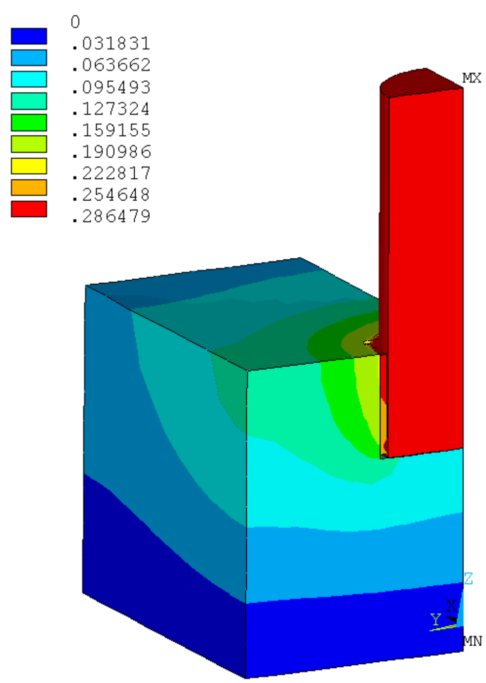


Figure 3: Model predicted voltage drop for the constant contact resistance setup (V)

For the second run, the pressure and temperature dependant contact resistance %table% setup was activated. The model voltage drop prediction in those conditions is 285 mV (see figure 4). The two runs predict about the same voltage drop indicating that the 2 micro-ohm m^2 is very close to the average contact resistance value for the second run, yet we can clearly see in figure 5 that is comparing the current density distribution in the cast iron that a significant redistribution of the current path has occurred.

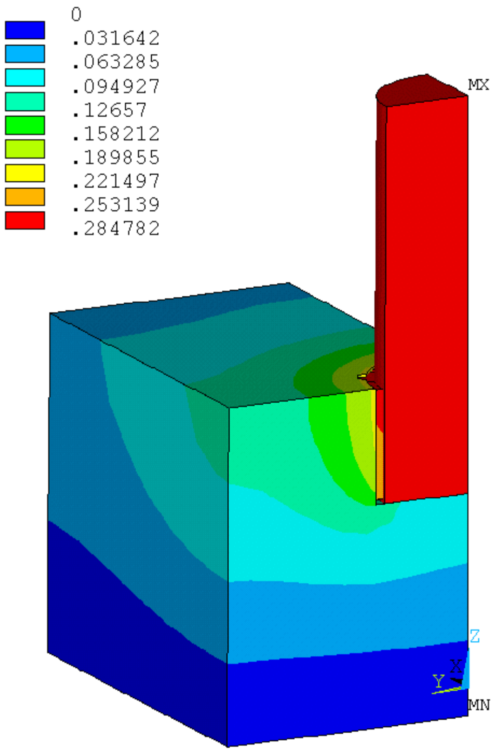
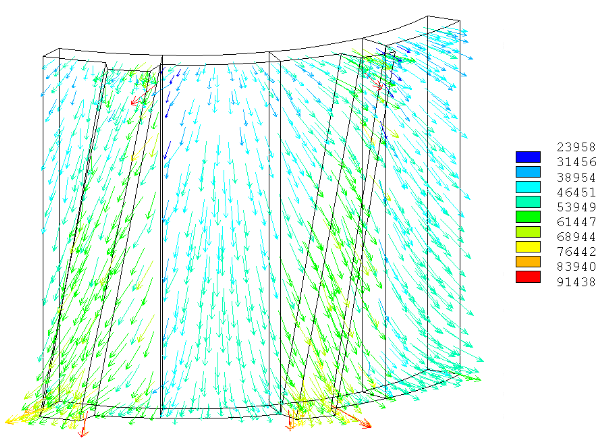
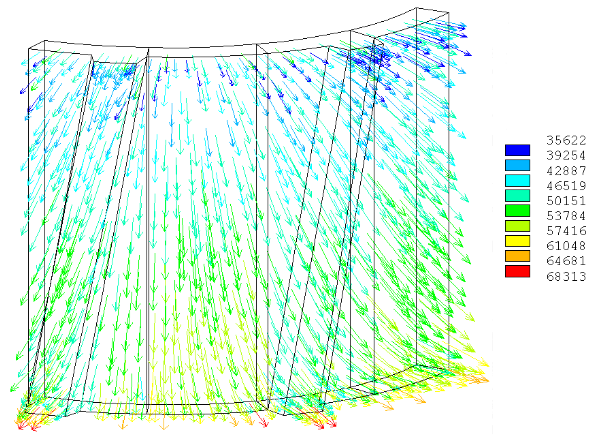


Figure 4: Model predicted voltage drop for the pressure and temperature dependant contact resistance setup (V)



Constant contact resistance model results



Pressure and temperature dependant model results

Figure 5: Comparison of the current density distribution in the cast iron between the constant contact resistance model setup and the pressure and temperature dependant model setup (A/m^2)

Second demonstration model

For the second demonstration model presented, the 16 flutes option was used (see cast iron mesh in figure 6). When using “classic” TE models with constant contact resistance setup, adding more flutes is always better because it is increasing the cast iron/anode carbon interface contact surface hence decreasing the predicted voltage drop regardless of the flutes geometry.

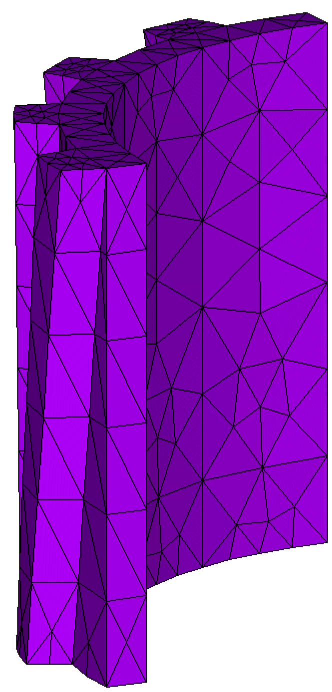


Figure 6: Quarter stub hole thermo-electro-mechanical model: cast iron mesh 16 flutes design

For this second demonstration model, the minimum cast iron thickness is reduced to 10 mm while keeping the same flute geometry except for the flutes depth that is increased to 10 mm keeping the same maximum 20 mm maximum cast iron thickness. The average cast iron thickness remains unchanged at 14 mm for this second case geometric setup.

The first run with the constant 2 micro-ohm m^2 contact resistance predicts 273 mV for the anode voltage drop, a reduction of 13 mV or 4.5% compared with the 8 flutes design constant resistance case reflecting the increased of the interface contact surface. This is very misleading because the run with the pressure and temperature dependant contact resistance setup ratter predicts 288 mV for the anode voltage drop which is 3 mV more than the 8 flutes variable contact resistance case. Hence according to the TEM model with the pressure and temperature contact resistance setup, adding more flutes, of that design at least, is not reducing the anode voltage drop, on the contrary, it is increasing it slightly. This slight increase of anode voltage drop prediction is quite consistent with what was reported in [8] for a very similar stub hole design change study.

Using the developed ANSYS® based TEM stub hole anode model as a design tool

These initial results demonstrate that the ANSYS® based TEM model is equally good as the FESh++ based TEM model, they are not highlighting the power of the ANSYS® based TEM model as an efficient design tool. First of all, the ANSYS® APDL model is parametric, which means that for a given model topology (per example the 8 flutes model option), it is possible almost instantaneously to edit the APDL model input file to change the model geometry (stud diameter, stud hole depth, minimum cast iron thickness etc.), the model material properties (carbon block thermal conductivity, cast iron thermal expansion coefficient, cast iron/anode carbon contact resistance etc.) or the model boundary conditions (amperage, bath temperature, bath immersion level etc.) and submit another run.

Next in importance after the model user friendliness, is the model turnaround time. Those quarter stub hole models (or 1/12 anode model for a 3 studs per anode design) solves in only around 4000 CPU seconds on a 64 bits dual core Intel Centrino T 9300 Cell Precision M6300 portable computer running ANSYS® 12.0 version. So this parametric ANSYS® based TEM anode stub hole model is a very efficient tool to study alternative flutes design per example.

Testing of a few flute design alternative quickly revealed that the most sensitive parameter in the flute design is the angle departure from the radial axe of the two side faces of the flute. This angle is an indirect parameter in the APDL model construction setup, it can be calculated to be 14º for the 8 flutes case (arctan((18-14)/2)/8)) and 11º for the 16 flutes case (arctan((18-14)/2)/10)). Detailed model results analysis revealed that those angles are too shallow to permit any significant pressure buildup on these two flutes side faces and that without a good pressure, essentially no current is passing through those contact interface surfaces because that without significant pressure, the interface contact resistance is much too high.

Once identified, this flute design weakness can be easily fixed. The third case presented here, is almost identical to the first case (8 flutes option), only the width of the flutes tip has been reduced from 14 mm to only 4 mm. With this change, the angle departure from the radial axe of the two side faces of the flutes is increased from 14º to 41º (arctan((18-4)/2)/8)). This time, the model predicts 290 mV of anode voltage drop for the constant 2 micro-ohm m^2 contact resistance setup run, reflecting the lost of contact surface compared with case 1. Once again, this is very misleading because the pressure and temperature dependant contact resistance model setup run ratter predicts 278 mV which is a 7 mV or 2.5% decreased obtained by that very simple flute design change (see figure 7 for the new flute design mesh, figure 8 for the cast iron/carbon anode contact pressure and figure 9 for the new cast iron current density).

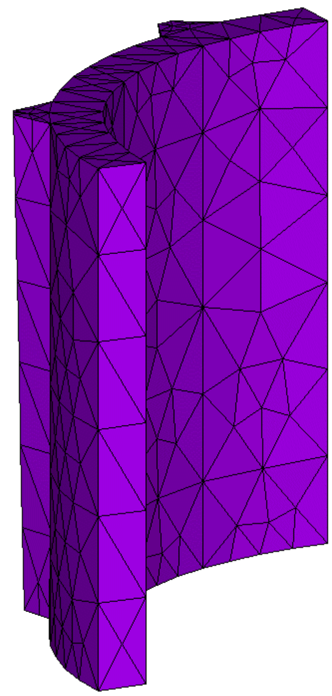


Figure 7: Quarter stub hole thermo-electro-mechanical model: cast iron mesh new 8 flutes design

Similarly, the forth case is a slight modification of the second case with 16 flutes, only the width of the flutes base has been increased to 20 mm and the width of the flutes tip has been reduced to 4 mm in order to get a 39º radial departure angle (arctan((20-4)/2)/10)) for the flutes side faces. The model predictions are 281 mV of anode voltage drop for the constant 2 micro-ohm m^2 contact resistance run and only 271 mV for the pressure and temperature dependant contact resistance run.

So when comparing the results obtained for the two 16 flutes cases, according the TEM model with the proper pressure and temperature dependant contact resistance setup, a very sight change in the flutes design aiming at increasing the contact pressure of the flutes side faces should decrease the anode voltage drop by 17 mV or 5.9% (see figure 10 for the total voltage drop, figure 11 for the cast iron/carbon anode contact pressure and figure 12 for the new cast iron current density). This represents a reduction of about 0.3 MM $ per year of operating cost for a typical modern smelter simply by changing the shape of the stub hole former! Of course, a much more detailed optimization study should be able to identify designs offering even more voltage drop reductions!

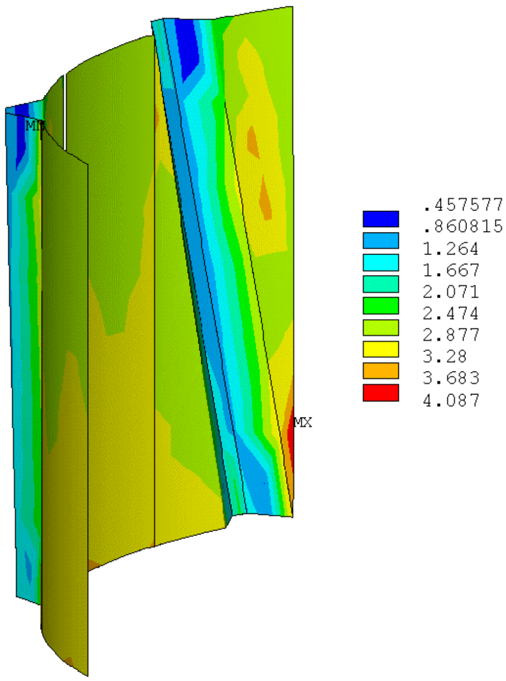


Figure 8 Cast iron/anode carbon interface contact pressure (MPa)

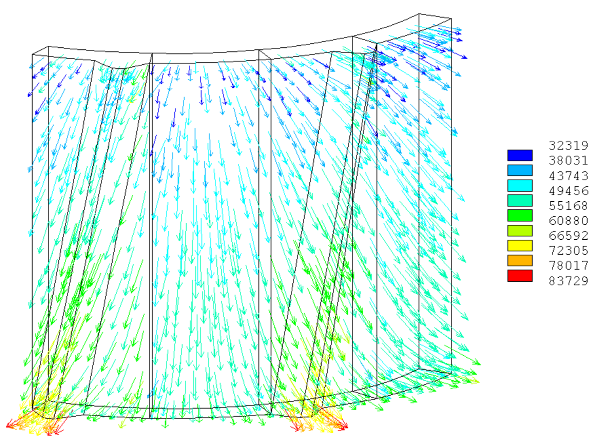


Figure 9: Current density distribution in the cast iron (A/m^2)

Conclusions

An ANSYS® version 12.0 based fully coupled TEM anode stub hole design tool have been successfully developed that is now available to the whole aluminium industry through GeniSim Inc.

The ANSYS® based APDL model is parametric, which means that for a given model topology, it is possible almost instantaneously to edit the APDL model input file to change the model geometry and submit another run.

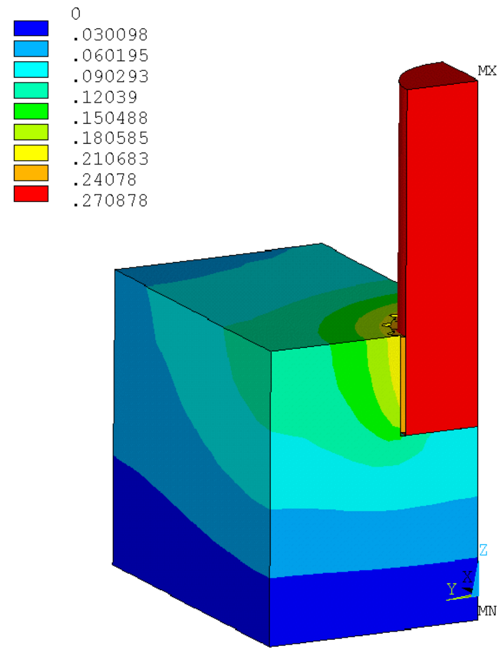


Figure 10: Model predicted voltage drop for the pressure and temperature dependant contact resistance setup (V)

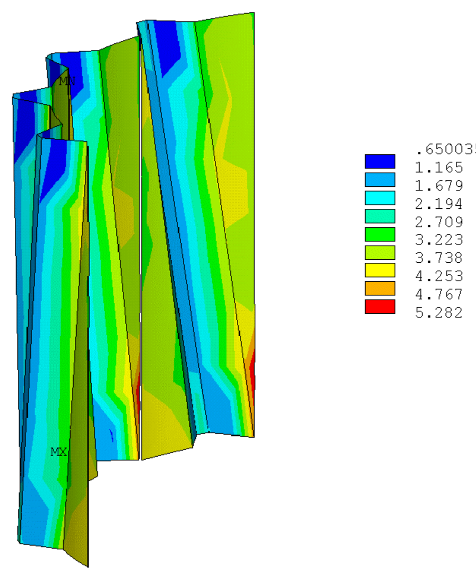


Figure 11 Cast iron/anode carbon interface contact pressure (MPa)

The quarter stub hole model presented here solves in only around 4000 CPU seconds on a 64 bits dual core Intel Centrino T 9300 Cell Precision M6300 portable computer running ANSYS® 12.0 version. So this parametric ANSYS® based TEM anode stub hole model is a very efficient tool to study alternative flutes design per example.

A very quick flutes design optimization study revealed that a very sight change in the flutes design aiming at increasing the contact pressure of the flutes side faces should decrease the anode voltage drop by 17 mV or 5.9% which represents a reduction of about 0.3

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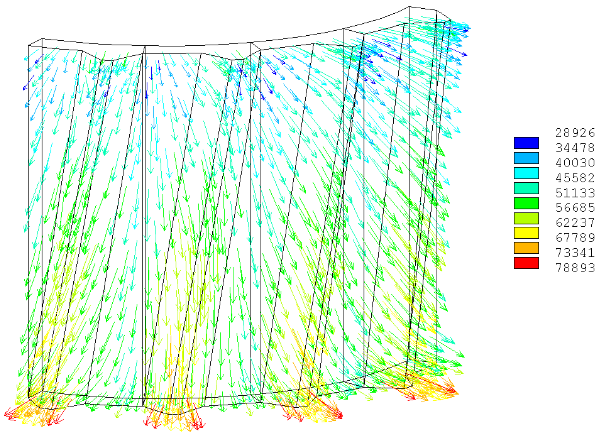

Figure 11: Current density distribution in the cast iron (A/m^2)

Acknowledgements

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