COMSOL Application To Estimate 3d Blast Furnace Hearth Wear Using Thermocouple Measurements

Yalcin Kaymak[1*], Thorsten Hauck[1], Jörg Mernitz[2], Rongshan Lin[3], Harald Rausch[3]
1. VDEh-Betriebsforschungsinstitut GmbH, Düsseldorf, NW, Germany
2. ArcelorMittal Eisenhüttenstadt GmbH, Eisenhüttenstadt, BB, Germany
3. AG der Dillinger Hüttenwerke, Dillingen, SL, Germany
* Corresponding author - email: yalcin.kaymak@bfi.de - tel: +49 211 6707 299

Introduction

The blast furnace is a counter flow reactor to produce pig iron. The molten pig iron and byproduct slag are accumulated at the hearth of the furnace, from where they are tapped regularly. The campaign life of the blast furnace is governed by the erosion of the hearth refractory. Once the residual thickness of the hearth lining is critically low, it must be repaired during a long-term stoppage which is quite costly. Therefore, it is essential to keep track of the residual lining thickness not only for the better planning of the relining but also for the operational safety (avoiding dangerous hearth breakthrough incidents) [1].

Modern blast furnaces are equipped with many thermocouples in the hearth refractory to monitor the temperature levels since the increasing values of temperature indicate decreasing lining thickness [2-6]. An inverse 3D heat transfer model has been developed to estimate the 3d hearth wear profile which fits best to the current thermocouple measurements on a daily basis. The LiveLink™ for MATLAB® has been utilized to interpolate and optimize the 3d wear profile from the wear parameters. Furthermore, a COMSOL® application has been programmed as a user interface to visualize the results.

Theory

Consider a general steady-state heat conduction problem defined on an arbitrary volume which has a fixed outer cooled boundary and an unknown shape inner heated boundary. The purpose of inverse geometry heat transfer problem is to determine the unknown shape of the hot side boundary for the given set of observed temperatures [2-6]. The geometry is described by Kriging technique [7] from a set of parameters which are the unknowns of the inverse geometry problem. That means the location of the unknown hot side boundary of the blast furnace hearth is parametrized by a set of n parameters $\mathbf{p}=(p_1,\ldots,p_n)$, the following optimization problem is posed as the inverse problem of finding the geometry parameters $\mathbf{p}^*$.

$$\mathbf{p}^* = \arg\min_{p\in\mathbb{R}^n} \frac{1}{2}\left\|\mathbf{T}(\mathbf{p}) - \mathbf{T}^{obs}\right\|$$

$\mathbf{T}^{obs}$ is the vector of the daily average thermocouple measurements. $\mathbf{T}(\mathbf{p})$ is the simulated temperature for the set of geometry parameters $\mathbf{p}$.

This optimization problem is solved using the Levenberg–Marquardt algorithm (LMA) [8]. The LMA, which is also known as the damped least-squares (DLS) method, is used to solve non-linear least squares problems.

Methods

COMSOL Multiphysics is used to compute the temperatures T(p) for a given set of geometry parameters $\mathbf{p}=(p_1,\ldots,p_n)$. The parameterization of the wear surface geometry is described by Kriging technique [7]. Kriging or Gaussian process regression is a method of interpolation for which the interpolated values are modeled by a Gaussian process governed by prior covariances. Under suitable assumptions on the priors, kriging gives the best linear unbiased prediction of the intermediate values. The method is widely used in the domain of spatial analysis and computer experiments.

The interpolation control points are placed on the initial wear surface with respect to thermocouple positions. The geometry parameters define the displacements of the control points at given directions. The initial wear surface is triangulated so that its movement can be described by the movements of the vertices. The movements of the vertices are interpolated from the movements of the control points.

In a daily scheduled way, the wear parameters are computed and saved automatically since every day a new $\mathbf{T}^{obs}$ vector is available as a set of average thermocouple measurements. It is also necessary to keep track of the evolution of the wear surface since previously eroded refractory lining should not be rebuilt in the model in any way.

The blast furnace operators need a user interface to visualize the computed hearth erosion and other results. The visualization of the results for a selected day is easily programmed, thanks to COMSOL Application development tools. Figure 1 shows an example, a typical user interface for monitoring the hearth lining state at a selected date. The operator can choose the date from a pull-down menu, and then click the Load button to update the results. The selection list on the left side allows switching between different predefined plots. Examples of 3d plots (see Figure 3) are temperature distribution on the steel shell, the residual lining thickness remaining or progress of wear and built-up of solidified material on inner surface, so-called skull. Examples of 2d plots are temperature contours on predefined vertical and horizontal cut planes (see Figures 4 and 5). Examples of 2d unrolled wall plots are temperature distribution on the steel shell, the residual lining thickness remaining or progress of wear and built-up of skull as well as the thermocouple data. Positions of thermocouples are shown with red points.

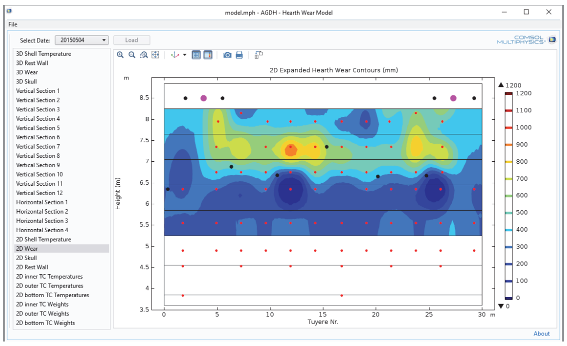

Figure 1. COMSOL® Application for visualisation of the computed hearth lining state.

The evolution of results and the temperature data is programmed using MATLAB®. As seen in Figure 2, the operators can select a vertical section using the radiobuttons. The drawing in the background shows the typical vertical section of the blast furnace hearth with the thermocouple positions marked by large red points. Not all thermocouples shown by the red points are installed for each section. A checkbox is shown if it is installed. To view the data related to a thermocouple (see Figure 5), the respective checkbox should be marked. The green arrows plotted in the background drawing show the directions for the wear parameters. In order to view the computed wear related data (see Figure 6), the checkbox positioned at the arrow head should be marked. The desired time evolution plot can be viewed by the corresponding pushbutton.

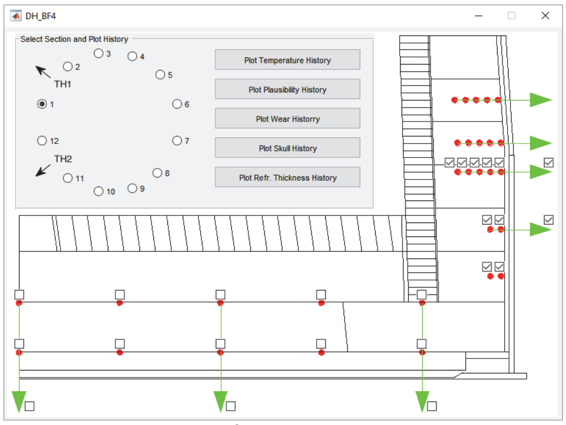

Figure 2. MATLAB® GUI to select TC and wear parameters for time evolution visualisation of data.

Results

The visualized results can be interactively zoomed, panned or tilted which gives the user a great freedom to evaluate the results in detail. Text annotations (such as taphole positions as TH1 and TH2, or selected section as S#) are used in COMSOL plots. Figure 3 shows the residual lining thickness contours at the inner face of the blast furnace hearth lining. The operators are usually interested in high wear regions which are colored in red in the selected legend color scheme.

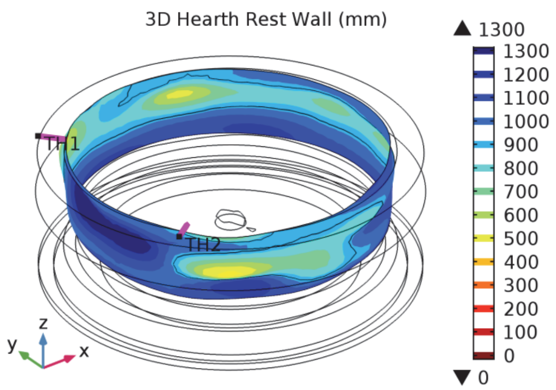

Figure 3. 3d hearth residual wall thickness.

Figure 4 and 5 show the temperature distributions in the vertical section 7 and horizontal section at elevation z=7.35m. The original lining positions are drawn with thin black lines. The operators usually go through all the vertical and horizontal sections to identify the wear progress and asses the safety of the remaining lining thickness for the current state of the furnace hearth.

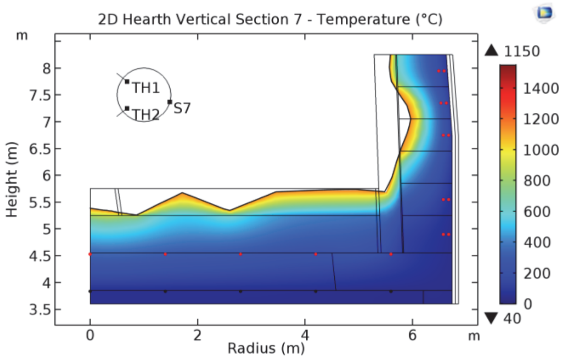

Figure 4. AGDH BF4 hearth vertical section 7.

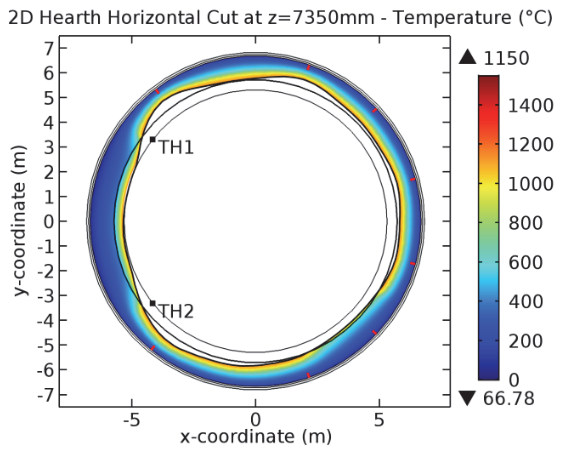

Figure 5. AGDH BF4 hearth horizontal section.

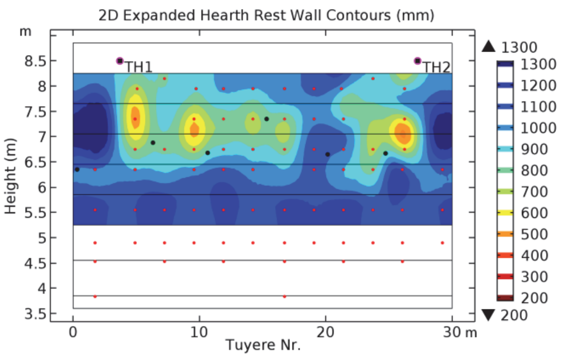

Figure 6. AGDH BF4 residual lining thickness unrolled.

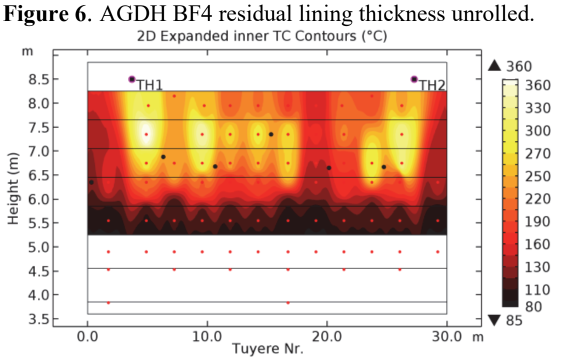

Figure 7. Interpolation of thermocouple values unrolled.

Figure 6 and 7 show the residual lining thickness and interpolated inner thermocouple temperature values as unrolled wall plots. As expected there are one-to-one correspondences between high temperature positions and high wear positions. The model converts temperature information to the directly usable residual lining thickness estimation.

The operators are interested in the time evolution of the temperature and wear progress. The MATLAB® GUI shown in Figure 2 provides this possibility. Figure 8 and 9 show the time evolution of measured temperatures and computed wear parameters. The operators have a great freedom to open multiple figures to zoom and pan the views so that the results can be compared and evaluated in detail. The time axis automatically updates the date tics for best readability when the view is zoomed. The legend is also shown in the figures to distinguish the plotted lines for different thermocouples or wear parameters.

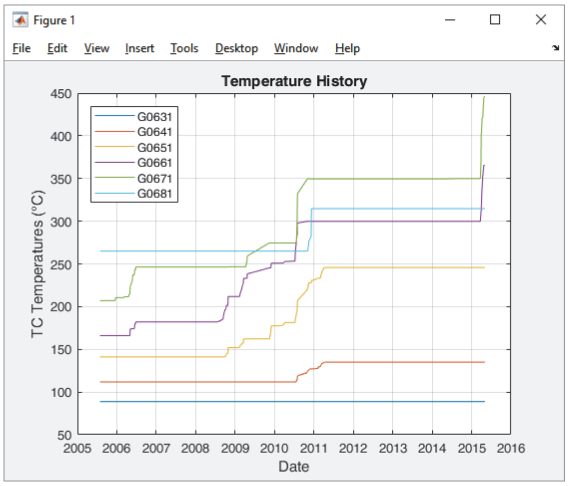

Figure 8. Time evolution visualisation of TC data.

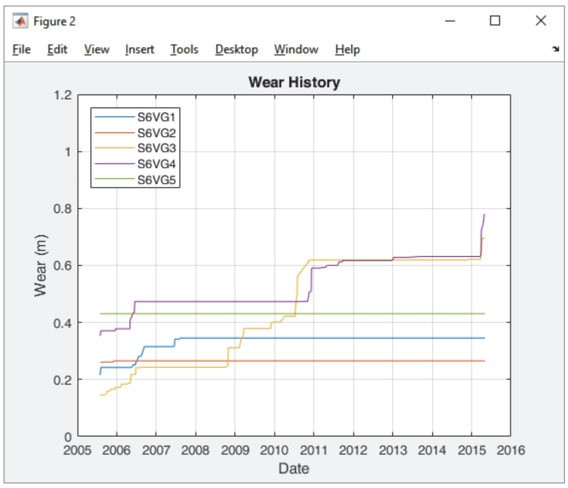

Figure 9. Time evolution visualisation of wear parameters.

Model Validation

The described model has been adopted for monitoring the blast furnace hearth lining state at two industrial plants at Dillinger Hüttenwerke and ArcelorMittal Eisenhüttenstadt. Both of these blast furnaces have been recently relined, which provides the opportunity to measure the residual lining thicknesses and compare them with the model estimations as a validation. Figure 10 shows the measured residual thicknesses on the technical drawing on the left side. The photos on the right side show how these measurements were made during the dissection. These observations revealed that the hearth lining suffers from embrittlement at both blast furnaces. Under certain conditions, the refractories may be degraded along the 800°C isotherm. Although in theory the wear surface is assumed to correspond to the 1150°C isotherm, the 800°C isotherm should be consider as wear surface when the brittle layers are built-up. Both relining observations have validated the developed model being in very good agreement with the computed 800°C isotherm.

Figure 10. AMEH BF5A hearth excavation measurements

Conclusions

Monitoring the state of the blast furnace hearth lining state is essential not only for the better planning of the relining but also for the operational safety (i.e. avoiding dangerous hearth breakthrough incidents). Modern blast furnaces are equipped with many thermocouples in the hearth refractory to monitor the temperature level which increases with the refractory wear.

An inverse 3D heat transfer model has been developed to estimate the 3d hearth wear profile which fits best to the current thermocouple measurements on a daily basis. COMSOL Multiphysics® and LiveLink™ for MATLAB® have been utilized to interpolate the 3d wear profile to solve the temperature field. The developed model is daily solved using COMSOL Server™ with MATLAB®. Furthermore, a COMSOL® application has been programmed as a user interface to visualize the results such as residual refractory thickness, temperature contours, historical evolution of wear parameters and temperatures, etc.

The blast furnace operators can access a variety of model results by just using a web browser. The most useful plots are residual refractory thickness contours plotted on the 3d hearth wear surface or on the 2d unrolled hearth wall, the temperature contours in a selected vertical or horizontal section through the hearth refractory lining, and the historical evolution of wear parameters and temperatures.

The developed model has been calibrated and validated by comparing the estimated wear profile with the measured residual wall thickness during the last relining at Eisenhüttenstadt and Dillinger plants.

References

1. J.v.d. Stel, et al., Blast Furnace Sustained Tapping Practice, SUSTAINTAP, *EUR 28066 EN* (2016)
2. M. Schulte, R. Klima, D. Ringel, M. Voss, Improved wear-control at the blast furnace hearth by direct heat-flux measurements. *Ironmaking Conference Proceedings*, 607-614 (1998)
3. M. Gonzalez, M. Goldschmit, Inverse geometry problem of estimating the location of the 1150◦C isotherm in a blast furnace hearth. *Mecanica Computacional,* Vol. XXIII, pp. 2365-2380 (2004)
4. M. Gonzalez and M.B. Goldschmit, Inverse geometry heat transfer problem based on a radial basis functions geometry representation. *Int. J. Numer. Meth. Engng* 65, 1243-1268 (2006)
5. K. Sorli and I.M. Skaar, Monitoring the wear-line of a melting furnace. *3rd Int. Conference on Inverse Problems in Engineering*, Port Ludlow, WA (1999)
6. K. Kurpisz, A method for determining steady state temperature distribution within blast furnace hearth lining by measuring temperature at selected points. *Transactions ISIJ 28:926-929* (1988)
7. S.N. Lophaven, H.B. Nielsen, J. Søndergaard, DACE a matlab Kriging toolbox. *Technical Report* IMM-TR-2002-12 (2002)
8. H.B. Nielsen, immoptibox a matlab toolbox for optimization and data fitting. *DTU Informatics, IMM* (2010)

Acknowledgements

The work presented here has been carried out with a financial grant from the Research Fund for Coal and Steel (RFCS) of the European Community with Grant Agreement No: RFSR-CT-2015-00001 and project title "Optimizing Blast Furnace Hearth Inner State" (OPTIBLAFINS).