Thermal assessment and identification of wear zones in a blast furnace hearth and tap-holes

H. Ghorbani, M. Al-Dojayli, and K. Chomyn
Hatch Ltd, Canada

The blast furnace hearth and tap-hole refractory system are exposed to harsh conditions during operation, due to chemical and physical degradation. These areas of experience high temperatures, thermal stress, chemical attack, and erosion due to fluid flow and steam oxidation. This makes the hearth, particularly tap-hole performance, critical to the overall blast furnace campaign life. Understanding the extent of refractory loss and the nature of the protective skull is important to avoid expensive repairs and to optimize production while extending campaign life. This paper describes a novel assessment methodology using Acousto Ultrasonic-Echo (AU-E) measurements and thermal data from thermocouples and the cooling system to predict a more accurate wear profile of the hearth and tap-hole refractory system while in operation. This method was also used for identification and confirmation of regions experiencing further wear over time. Transient heat transfer analysis was completed to determine the thermocouple response time to operational changes or events in the furnace. 2D and 3D analysis was used to gather a better understanding of the problematic areas in the blast furnace hearth.

Keywords: Blast furnace, hearth, tap-hole, refractory wear, skull formation, NDT, thermal assessment, thermocouple.

INTRODUCTION

Blast furnace hearth refractories are exposed to harsh conditions during operation, causing chemical and physical degradation, particularly in the tap-hole region during the tapping process. These regions of the hearth experience high temperatures, erosion due to fluid flow, thermal stress, chemical attack, and steam oxidation. The hearth performance, including the tap-holes, is a key factor in the overall blast furnace campaign life (Silva *et al*., 2012). Therefore, understanding the extent of refractory damage in this region is important to avoid expensive repairs, optimize production, and extend the campaign life. This paper describes the combination of two nondestructive techniques, namely stress wave analysis (Acousto Ultrasonic-Echo technology, or AU-E) (Filatov *et al*., 2016) and heat transfer analysis using refractory thermocouple and cooling system measurements. This combined thermal assessment using AU-E measurements and thermal data is used to obtain a more accurate prediction of the wear profile of the blast furnace hearth and the tap-hole regions.

BACKGROUND

Inverse geometry heat transfer modelling is often used for assessing refractory wear. Assuming 1D heat transfer between a group of linearly aligned thermocouples, the thickness of the remaining refractory in the hearth and at the tap-hole is extrapolated based on the thermal properties of the system. The thickness of the protective skull can also be estimated using the 1D heat transfer analysis considering thermocouple history (Silva *et al*., 2012) .

Temperature measurements and their respective positions are the only ongoing data required for the inverse geometry method. Analysis is simple and inexpensive as solutions can be generated through an online monitoring system. Disadvantages of this method include the inaccuracy of assuming 1D heat transfer in some regions of the hearth and nominal thermal material properties, location, and lateral distribution of thermocouples, and in many cases, a lack of continuously reliable thermocouple data. Hearths experience significant 2D and 3D heat transfer due to their cylindrical shape and complex construction which influences the predicted refractory thickness and skull formation. In addition, the extreme temperatures and chemical degradation that can occur in the blast furnace and around the tap-holes can alter the thermal properties of the refractory over time. Short-term operational changes may not be visible in the thermocouple data due to the thermal inertia of the furnace refractories. The limitations and assumptions of the inverse geometry method using one group of thermocouples at a particular measurement time create multiple possible combinations of refractory and skull thicknesses. Determining which condition exists in the hearth wall based only on a group of thermocouples is difficult due to complex wear mechanisms, and the thermal and structural behaviour of the hearth.

Using AU-E and thermocouple/cooling system measurements together allows for a more accurate prediction of the hearth condition. The AU-E data is used to eliminate substantial uncertainty in the overall prediction from refractory temperature measurements by determining the remaining refractory thickness at specific locations in an operating furnace.

AU-E technology is a nondestructive technique which can be used during blast furnace operations to predict skull and hearth refractory thickness using stress waves. First, a mechanical impact is applied to the surface of the structure to generate a stress pulse. The wave propagates through the various refractory layers and is partially reflected where the material properties of each layer change. The reflected waves are received and analysed to detect anomalies and estimate the refractory and skull thickness at the time of measurement (Silva *et al*., 2012; Sadri *et al*., 2015.

In the combined thermal assessment, a 2D model of the hearth refractory thickness is created using the AU-E and thermocouple data. Thermocouple readings in a specific region of interest are used as objectives simultaneously in an iterative optimization procedure to produce a skull and/or future wear profile which most accurately represents the temperatures recorded from the hearth wall and bottom and around the tap-holes.

In order to more accurately predict the hearth status, the combined thermal approach considers the change in thermal properties due to chemical attack on the brick. As shown in Figure 1, the hearth is exposed to zinc/alkali chemical attack when the refractory is exposed to temperatures above 850°C (Dzermejko, Baret, and Hubble, 1999).

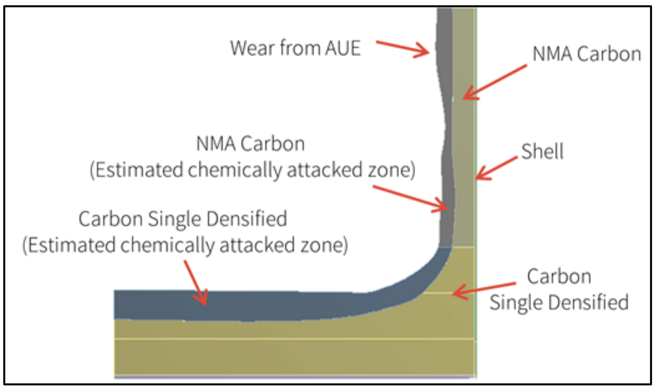


Figure 1. Refractory wear and chemically attacked zone.

A 1D thermal calibration along with AU-E data is used to determine the reduction in conductivity based on the original conductivity of the materials. The conductivity of the chemically attacked zone is approximately two-thirds of the original refractory conductivity (Campos *et al*., 2011). Since this estimate is for carbon refractory material, the calibration may need to be repeated for different refractory materials and/or a sensitivity analysis required to evaluate the effect on the refractory thickness estimate.

REFRACTORY WEAR AND SKULL PREDICTION

The combined AU-E and heat transfer model can be used throughout the furnace life to predict wear profiles and inform important decisions regarding the blast furnace operations. In the example presented here, specific regions of the operating blast furnace were analysed by constructing 2D sections of the furnace hearth.

The first section of the blast furnace analysed is a relatively typical region of the furnace away from tap-holes, shown in Figure 2. For this facility, the centre of the hearth is not accessible for AU-E measurements. A 'flat bottom' uniform wear profile of the hearth bottom is initially assumed, based on extrapolating the lowest available AU-E measurement taken on the hearth wall.

Using the flat bottom wear profile, the predicted skull from the combined thermal analysis and AU-E measurements is shown in Figure 2a. The skull is very thin at the centre of the hearth bottom, indicating a possible increase of wear in this area. Therefore, the analysis was repeated with an anticipated dish-shaped wear at the centre of the furnace, illustrated in Figure 2b. The model-predicted thermocouple temperatures predicted by this wear profile are aligned with those observed in the plant thermocouple data.

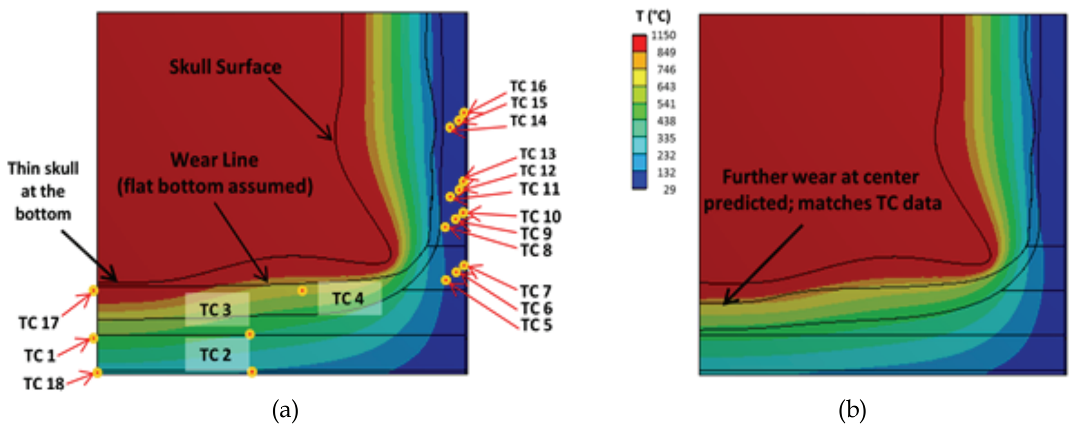


Figure 2. Prediction of (a) the skull thickness and (b) anticipated dish-shaped wear at the centre of the furnace, using combined thermal and AU-E method.

The heat flux calculated from the 2D thermal models was also compared to the heat flux through the side and bottom cooling systems. The comparison showed reasonable alignment, considering the expected accuracy of cooling system heat flux calculations and thermocouple data. The average heat flux provided by the cooling system is significantly influenced by small measurement errors since delta-temperature values through the staves/jacket or bottom cooling tend to be quite low. Nonetheless, the comparison provides a verification of the predictions.

The observed hearth temperatures increased significantly over the six-month period following the initial AU-E measurements. A combined thermal analysis was completed to compare monthly temperature peaks with the predicted skull formation and/or further wear over the intervening period. The estimated skull thickness at the beginning and end of this period is shown in Figure 3a.

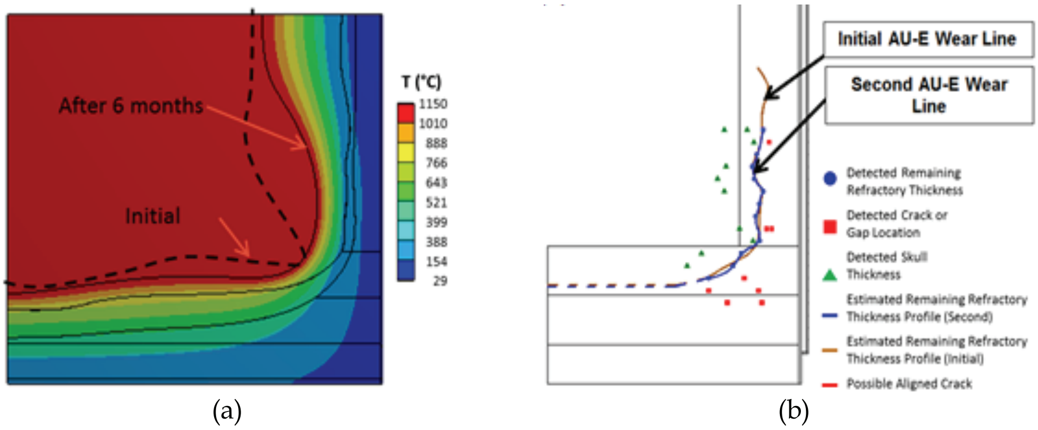
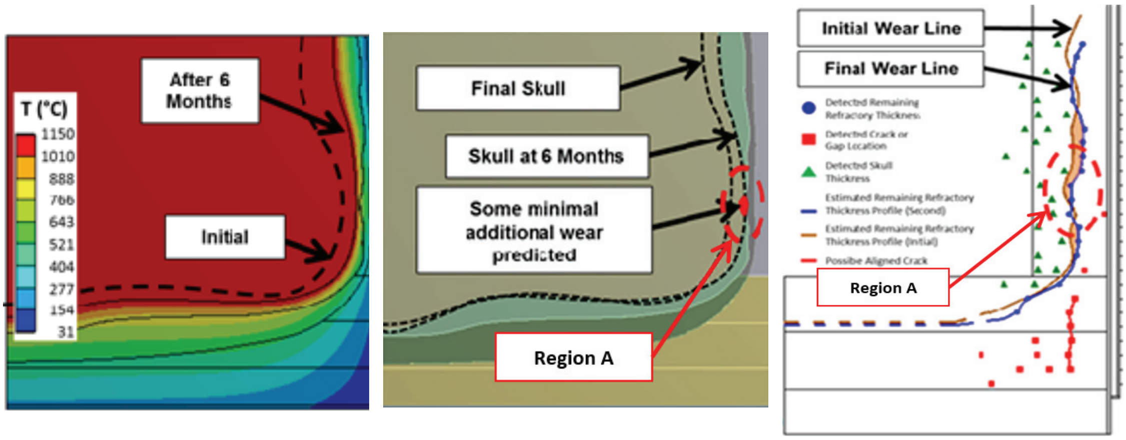


Figure 3. Skull thickness changes (a) predicted over a six-month period and (b) AU-E wear measurements over time.

Over the six-month period, the predicted skull thickness decreased. However, in most regions a substantial skull was still present, preventing any wear to the refractory bricks. Additional AU-E measurements were completed for this furnace one year after the initial measurements. For the most part, the AU-E showed negligible changes to the wear profile, as shown in Figure 3b, consistent with the thermal predictions.

In the same blast furnace, higher temperatures were recorded on the other side of the hearth, as shown in Figure 4a. The resulting skull prediction, seen in Figure 4b, shows almost no skull remaining and some areas of local additional wear based on the peak temperatures. The predictions suggest some, but not substantial, refractory wear in this area during the year. To approximate the extent of wear in the hearth, this analysis considered the daily temperature peaks. To provide guidance to the furnace operators and help to extend the campaign life, warning temperatures were also established using this model.

For the higher temperature section, for which wear was predicted from the thermal assessment, a comparison with AU-E is shown in Figure 4c. For this section, the AU-E measurement showed a small but notable amount of additional refractory wear in region A (circled in red, consistent with the prediction from thermocouple temperatures. This alignment is very good, considering the expected accuracy of the two techniques. Overall, the comparison between AU-E measurement and thermal wear predictions provides a verification of both methods.



(a) (b) (c)

Figure 4. Predictions for section B: (a) higher temperatures show skull thinning, (b) skull thickness estimates additional wear, and (c) AU-E measurements compared to predictions.

TRANSIENT ANALYSIS IN HEARTH BOTTOM

A transient heat transfer analysis was carried out to determine the response time of the thermocouples to operational changes or events in the furnace such as a sudden loss of skull. This analysis considers the thermal mass of the system. To illustrate the effect of the thermal mass and the importance of thermocouple layout, a local corner of the hearth relatively far from the thermocouple locations was examined (as seen in Figure 5a). The effect of a sudden loss of skull was simulated and the expected refractory temperature response was analysed over a 24-hour period, shown in Figure 5b. The change in the location of the identified isotherm is relatively small over the 24-hour period considered; the isotherm moves just slightly towards the refractory cold face. These results show that there is a significant delay before the thermocouples fully react to the change in skull thickness, as seen in Figure 6. In comparison, if the furnace had been designed with two additional thermocouples, TC-A and TC-B, the skull loss event would be more readily identified. TC-A records a 10% change in temperature one hour after the skull loss event occurs.

These results indicate that if a skull is quickly lost and/or quickly rebuilt, the thermocouple reading will have a delayed response, or may not show any substantial response. For example, if the skull is removed and begins to rebuild within a four-hour period, the existing thermocouples will read a minimal change in temperature, as seen in Figure 5b. The additional thermocouples located to monitor the corner of the hearth provide a more rapid response and will read a substantial change one hour after skull loss.

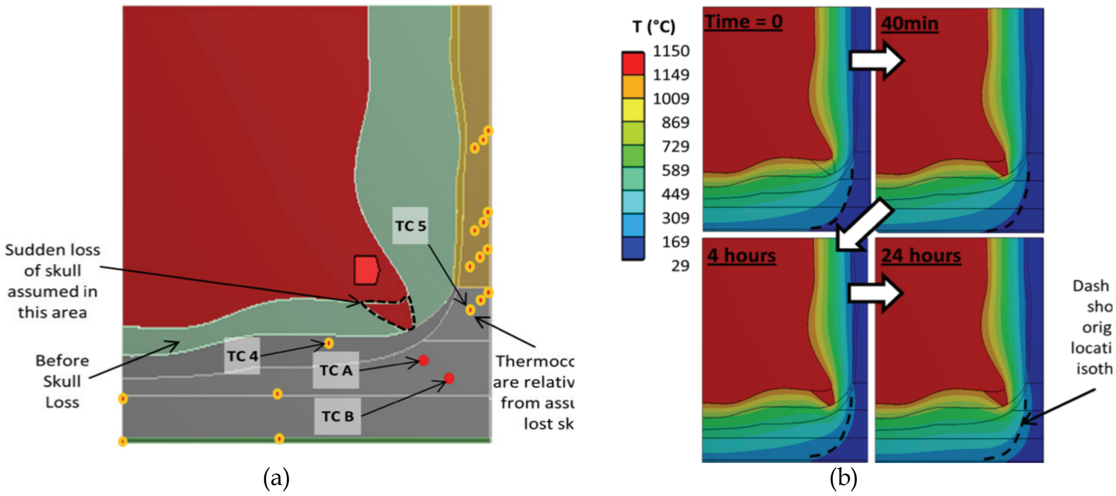


Figure 5. Transient analysis: (a) set-up and thermocouple layout, with (b) resulting temperature distribution over time.

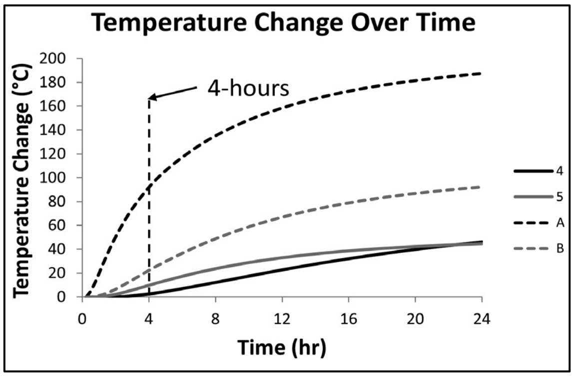


Figure 6. Delayed thermocouple temperature response due to sudden change in skull thickness.

The two thermocouples located in the hearth corner also show that the distance of the thermocouple from the hot face affects the thermocouple's ability to detect transient events. TC-A is located very close to the hot face and begins to register the skull loss event immediately, while TC-B experiences a short lag before reacting to the skull loss. In this furnace, the thermocouples are located relatively close to the cold face, as seen in Figure 2a, which makes them less able to detect high temperature events during early stages of hearth wear.

In many hearth designs thermocouples are not located in this bottom corner. This is likely because heat transfer in this area has significant 2D effects, so 1D heat transfer calculations are less reliable. However, by applying 2D assessment techniques these thermocouples can add significant value to the thermal assessment, particularly considering that the corner regions often undergo the highest wear (known as an 'elephant foot' wear pattern).

TRANSIENT ANALYSIS IN HEARTH SIDEWALL

To investigate the sensing efficiency of changing the depth of the thermocouples within the hearth sidewall, three 'shallow' thermocouples, TC-C, TC-D, and TC-E (as per the original hearth design) are compared with three 'deep' thermocouples TC-i, TC-ii, and TC-iii.

The placement and depth of the thermocouples are shown in Figure 7. This investigation considers the effect of an instantaneous skull loss and some additional wear at the location of the skull loss.

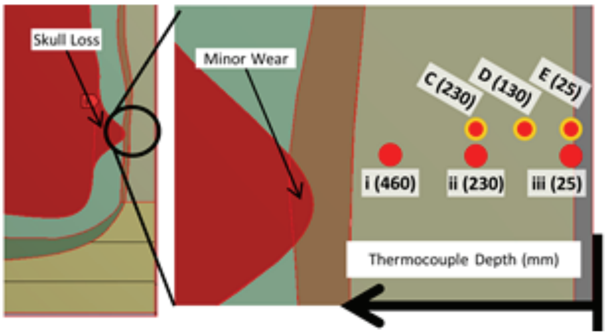


Figure 7. Placement of two sets of thermocouples within the refractory wall.

The skull loss event in this case can be identified fairly well by 1D heat transfer analysis. This analysis depends on the temperature difference between two thermocouples. Therefore, an effective thermocouple set-up is one in which the temperature difference between two adjacent thermocouples rapidly tends towards the new steady-state value caused by the skull loss. As seen in Figure 8, the deep thermocouples respond to the skull loss more rapidly than the shallow thermocouples. The deep thermocouples reach 95% of their steady-state reading after only 1 hour, indicating that 1D steady-state heat transfer analysis can be used to describe the behaviour of the skull/wear over that period. In contrast, the shallow thermocouples take four hours to reach 95% of their steady-state temperature difference, so short-term transient conditions in the furnace of one or two hours won't be captured, and the remaining refractory thickness will be over-predicted. This effect will be particularly prevalent during the early stages of the furnace life, when there is a thicker refractory layer. However, adopting a deep thermocouple layout will result in fewer thermocouples being available towards the end of the campaign. To accommodate the need for good thermal data at both the beginning and end of the campaign, alternating deep and shallow sets of thermocouples could be installed around the blast furnace.

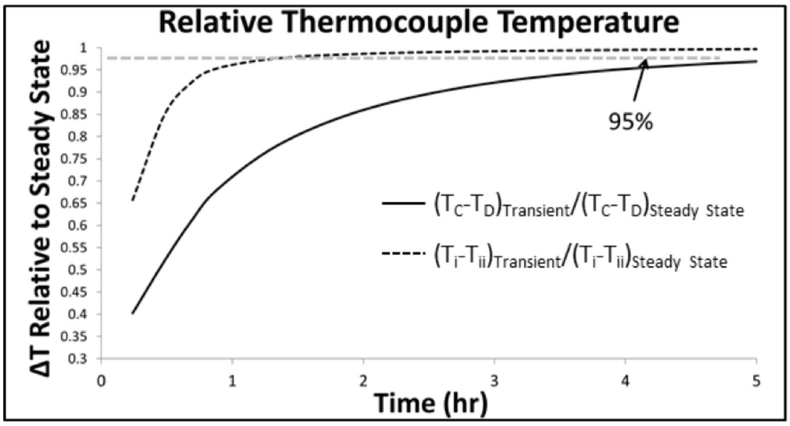


Figure 8. Transient response of thermocouple pairs.

3D REFRACTORY WEAR AND SKULL REPRESENTATION FOR HEARTH AND TAP-HOLES

Certain areas in the blast furnace hearth, particularly around the tap-holes, experience irregular wear due to the complex nature of the erosion, whether it is due to fluid flow, thermal stress, chemical attack, and/or steam oxidation. Better understanding of some of these aspects can be obtained using a 3D representation of the hearth. In this case, local hot-spots can first be identified in thermocouple measurements. Thermal analysis can then be used for the accurate calculation of the 3D refractory wear and skull profile distribution, considering the full set of thermocouple data simultaneously.

Figure 8 shows the temperature distribution and the estimated refractory and skull profiles with the tap-hole closed and open. Furthermore, several 2D sections of the hearth wall can be analysed according to their thermocouple data and then used to construct the 3D representation of the hearth. This approach provides conservative thickness estimates of the wear and skull that can be further assessed in 3D analysis. Figure 9 shows the assembly of several hearth wall segments with developed skull profile.

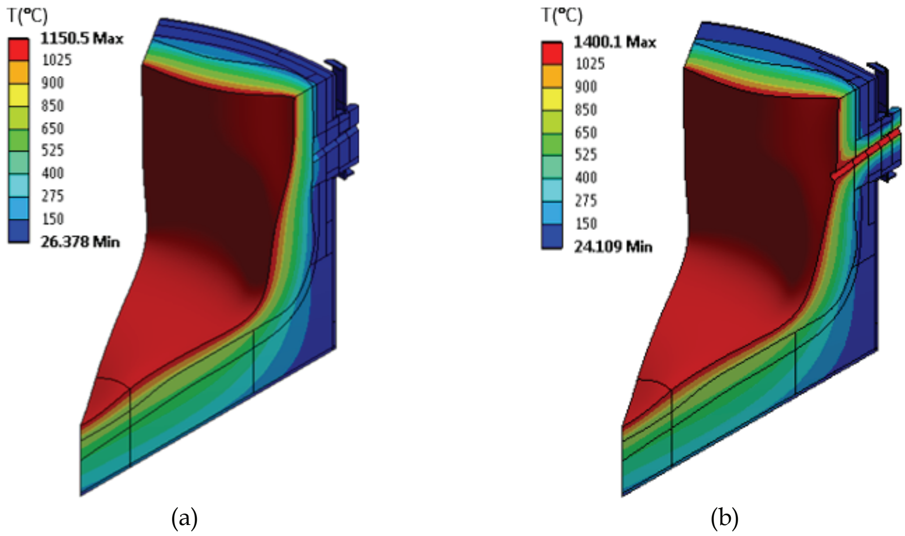


Figure 9. 3D representation of refractory wear and skull with tap-hole (a) closed and (b) open.

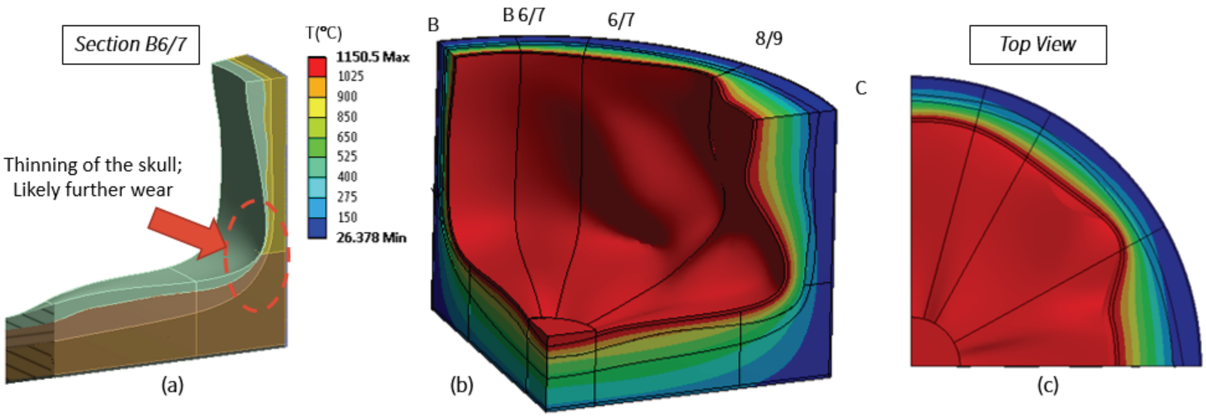


Figure 10. 3D representation of refractory wear and skull:
(a) 3D section, (b) assembly of 3D sections, and (c) top view of assembly.

CONCLUSION

AU-E measurement and thermal assessment of thermocouples and stave heat flux were used to identify wear within a blast furnace hearth, including tap-hole areas, for the purpose of a campaign life extension programme. AU-E measurements were taken at the beginning and end of a year of blast furnace operation. The initial measurement provided a remaining refractory thickness profile. During the following year, the blast furnace hearth temperature data was monitored and a hot-spot was identified. This higher temperature period was assessed and it was determined that within some regions of the blast furnace hearth the protective skull layer had been lost and a small amount of additional refractory wear was experienced. This was due to process changes, including an increased production rate. In other regions of the blast furnace hearth, the temperatures were lower. This suggested there had not been any additional refractory wear nor complete loss of the protective skull, due to preferential hot metal flow patterns towards one side of the hearth. These conclusions were later verified by the second AU-E measurement one year after the first. The AU-E and heat transfer assessment showed close alignment, providing a verification of the thermal assessment. The combination of the two methods enables the hearth wall and bottom conditions to be assessed with greater accuracy.

AU-E measurement often provides a more accurate determination of furnace refractory wear at a given point in time as it does not rely on thermocouple temperature history, which is sometimes not available or unreliable due to instrument error or plant data logging practice. Heat transfer assessments can be used to identify periods of refractory wear and a make reasonable estimate of the extent of the wear. The results are compared with other blast furnace operating parameters to identify correlations and determine the cause of hearth refractory wear. Operational recommendations can be made to prevent further wear and to prolong the hearth campaign life, delaying costly relining and downtime.

Careful selection of thermocouple locations is a critical part of hearth design. The thermocouples must be appropriately located to capture the transient and irregular wear that occurs within the furnace hearth. To assess the effect of thermocouple layout, transient and steady-state analyses were completed. The transient heat transfer assessment showed that the thermal mass within the hearth refractory will cause a slow response in the hearth to a sudden loss of skull. It may take a few days before a new equilibrium is reached. Therefore, a temporary loss of skull may not be identified by thermocouple temperatures if they are measured away from the region of skull loss. Slower events are less sensitive to thermocouple depth. Thermocouple locations should be selected carefully to ensure they can serve their function of monitoring the furnace health both at the start and towards the end of the hearth campaign life. Thermal assessment can be used to quantify the performance of a given thermocouple layout to ensure a cost-optimized design is selected.

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Hamid Ghorbani
Practice Lead – Specialised Engineering Analysis & Design, Hatch
Technical leadership role in several projects at Hatch and 20 years of experience in design, optimization. and fitness-for-service assessment of equipment and structures with complex geometry, material, and operating conditions for metallurgical smelters, power plants, and petrochemical facilities.