ASSESSMENT OF HEARTH REFRACTORY WEAR IN OPERATING BLAST FURNACES*

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ABSTRACT

The refractory system in blast furnace hearth is subject to harsh conditions including chemical attack and thermal / mechanical loads. The longevity of hearth is vitally important in achieving the target furnace campaign life and avoiding premature and costly repairs. Consequently, it is important to monitor the hearth refractory wear including the temperature distribution andprotective skull formation. This paper presents a novel approachto simultaneously utilizeAcousto-Ultrasonic Echo (AU-E) non-destructive examination and thermocouple / cooling system data to improve accuracy of hearth refractory wear predictions in operating blast furnaces. Example applications of this assessment methodology on blast furnaces are discussed. This assessment methodology is widely used to help prolong the blast furnace campaign life.

Keywords: Blast Furnace, Hearth, Refractory, Wear, NDT, Thermocouple.

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* *Technical contribution to the 48º Seminário de Redução de Minério de Ferro e Matérias-Primas e 6º SimpósioBrasileiro de Aglomeração de Minério de Ferro, part of the ABM Week, October 2nd-4th, 2018, São Paulo, SP, Brazil.*

1INTRODUCTION

Blast furnace hearth refractory is exposedto harsh conditions during operation including chemical and physical degradation. The blast furnace hearth experiences high temperatures, erosion due to fluid flow, thermal stress, chemical attack, and steam oxidation. The hearth performance is key to the overall blast furnacecampaign life [1].Therefore, understanding theextent of refractory damageis importantto avoid expensive repairs and to optimize production and extend the campaign life.This paper describes the combination of two non-destructive techniques: stress wave analysis (Acousto Ultrasonic-Echo technology, AU-E)[2] 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 more accurately predict the wear profile of the hearth while in operation.

2BACKGROUND

Inverse geometry heat transfer modelingis often usedfor assessing refractory wear.Assuming 1D heat transfer between a group of linearly aligned thermocouples, the thickness of the remaining refractory 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 [1].

Temperature measurements and their respective positions are the only ongoing data measurement required for the inverse geometry method.Analysis is simple and inexpensive as solutions can be generated through an online monitoring system. Disadvantages to this method include the inaccuracy of assuming 1D heat transfer in some regions of the hearth and nominal thermal material properties, 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 can influence/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. 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 thickness. Determining which condition exists in the hearth wall based only on a group of thermocouples is difficult due to complex wear mechanisms, and thermal and structural behavior of the hearth.

AU-E technology is a non-destructive technique which can be used during blast furnace operations to predict skull and 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 by the change in material properties of each layer. Theresulting compressive waves are reflected, received, and analysed to detect anomalies, and estimate the refractory and skull thickness at the time of measurement [1][3].

Using AU-E and thermocouple / cooling system measurements together allows for a more accurate prediction of the entire 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.
In the combined thermal assessment, a 2D model of the hearth refractory thicknessis createdusing the AU-E and past 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.

In order to more accurately predict the hearth status, the combined thermal approach considers the change in thermal properties due to the chemical attacks on the brick. As shown in Fig. 1, the hearth is exposed to zinc/alkali chemical attack when the refractory is exposed to temperatures above 850°C (various references, including [4]).

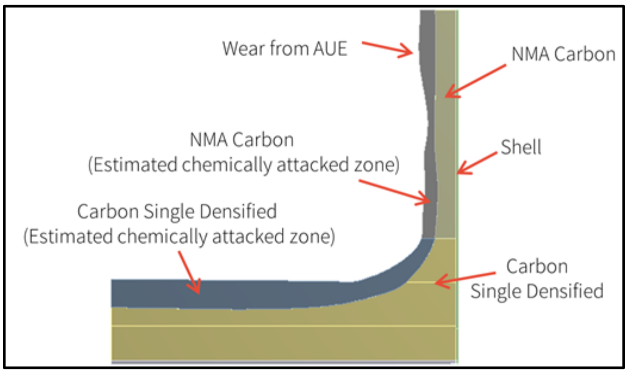

Fig. 1:Refractory wear and chemically attacked zone

A 1D thermal calibration is used to determine the reduction in conductivity knowing the original conductivity of the materials. The reduction in conductivity of the chemically attacked zone is consideredto be about two thirds of the original refractory conductivity for the blast furnace analyzed in this paper [5].

3REFRACTORY WEAR AND SKULL PREDICTION

The combined AU-E and heat transfer model can be used throughout the furnace life to predict wear profiles and make important decisions regarding the blast furnace operations. In the example presented here, specific regions of the operating blast furnace were analysed by making 2D sections of the furnace hearth. The first section of the blast furnace analyzed is Section E. For this facility, the center 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 Fig. 2(a). The skull is very thin at the center 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 center of the furnace, illustrated in Fig. 2 (b).The model-predicted thermocouple temperatures predicted by this wear profile are aligned with those observed in the plant thermocouple data.

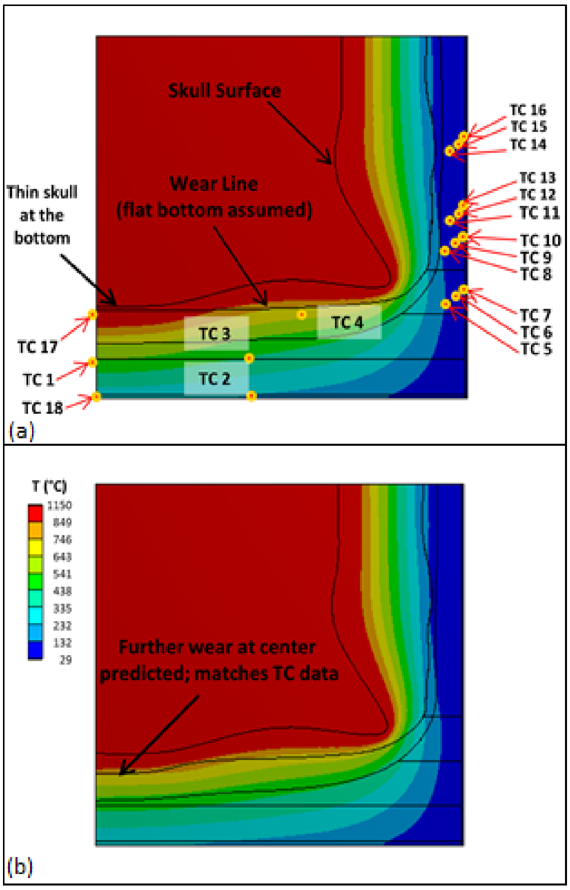

Fig.1: Predicting, using combined thermal and AU-E method,(a) the skull thickness and (b) anticipated dish-shaped wear at the center of the furnace

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. In particular, the average heat flux provided by the cooling system is significantly impacted 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. Section E represents a relatively typical region of the furnace, and is shown in Fig. 3(a) at the beginning and end of this period.

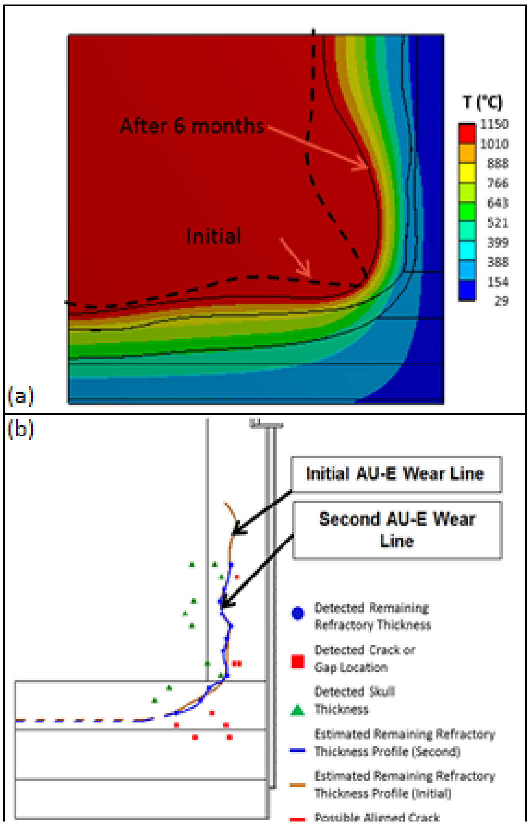

Fig. 3: Skull thickness changes predicted: (a) over a six-month period and(b)AU-E wear measurements over time

Over the six-month period,the predicted skull thickness decreased. However, within 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 Fig. 3(b), consistent with the thermal predictions.

The same blast furnace had higher temperature recordings on the other side of the hearth, Section B, as shown in Fig. 4(a).The resulting skull prediction, seen in Fig. 4(b), shows nearly 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 helping to extend the campaign life, warning temperatures were also established using this model.

For the higher temperature Section B, for which wear was predicted from the thermal assessment, a comparison with AU-E is shown in Fig. 4(c).For this section, the AU-E measurement showed a small but notable amount of additional refractory wear; as seen circled in red, this was 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.

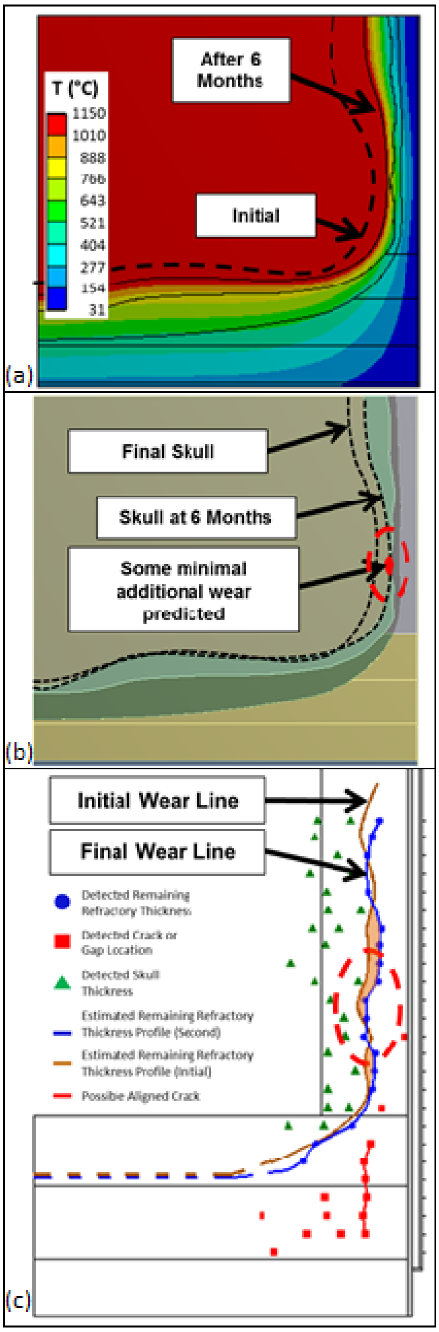

Fig. 4: Predictions for Section B: (a) Higher temperatures show skull thinning, (b) skull thickness estimates additional wear and (c) AU-E measurementscompared to predictions

4TRANSIENT ANALYSIS IN HEARTH BOTTOM

A transient heat transfer analysis was investigated 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 Fig. 5(a)). The effect of a sudden loss of skull was simulated and the expected refractory temperature response was analyzed over a 24-hour period shown in Fig. 5(b).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 actual thermocouples fully react to the change in skull thickness as seen inFig. 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 experiences 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 have 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 Fig. 5(b). 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.

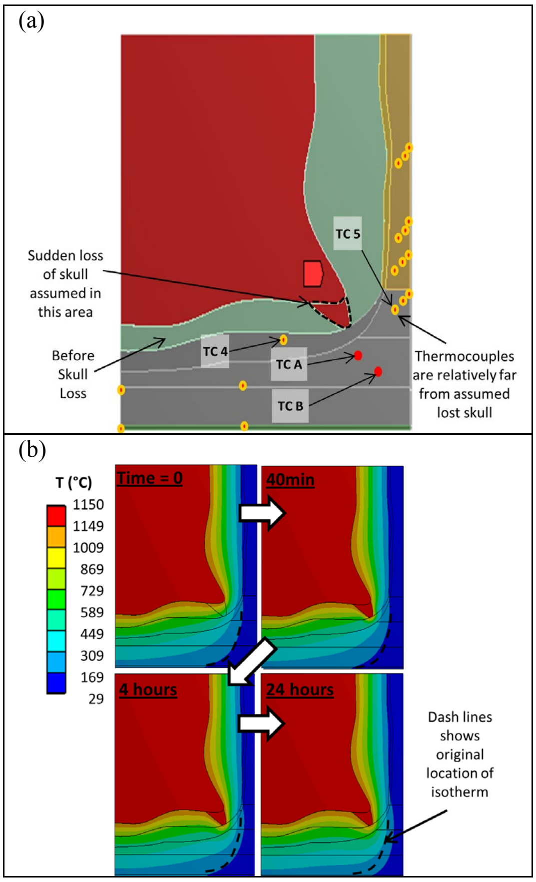

Fig. 5: Transient analysis (a) setup and thermocouple layout with (b) resulting temperature distribution over time

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 particular furnace, the thermocouples are located relatively close to the cold face, as seen in Fig. 2(a), 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 due to the fact that 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 the corner regions often see the highest wear (known as an “elephant foot” wear pattern).

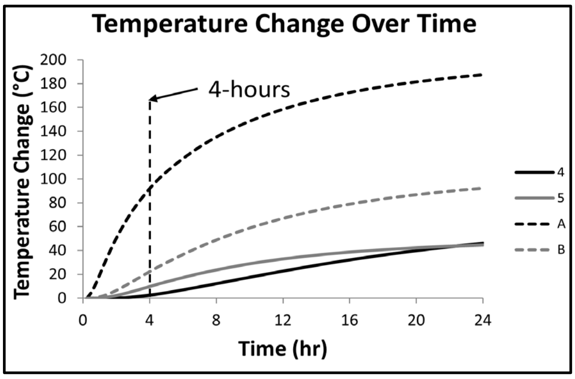

Fig. 6: Delayed thermocouple temperature response due to sudden change in skull thickness

5TRANSIENT ANALYSIS IN HEARTH SIDE WALL

To investigate the sensing efficiency of changing the depth of the thermocouples within the hearth side wall, 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 is shown in Fig. 7. This investigation considers the effect of an instantaneous skull loss and some additional wear at the location of the skull loss.

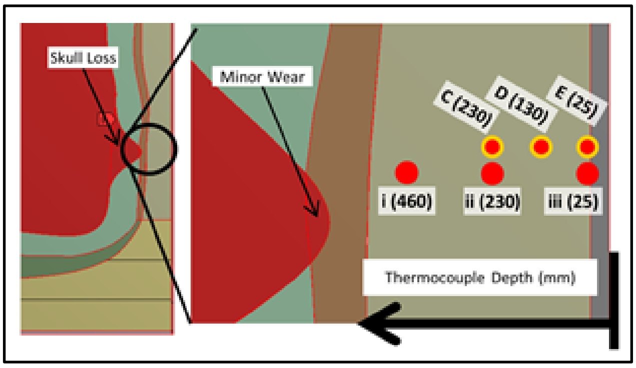

Fig. 7: Placement of two sets of thermocouples within the refractory wall

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 setup is one where the temperature difference between two adjacent thermocouples rapidly tends towards the new steady state value caused by the skull loss. As seen in Fig. 8, the deep thermocouples respond to the skull loss more rapidly than the shallow thermocouples. The deep thermocouples achieve 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 time period. In contrast, the shallow thermocouples take four hours to achieve 95% of their steady-state temperature difference, so short-term transient conditions in the furnace of one – 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 availabletowards the end of the campaign. To accommodate the need for good thermal data at both the beginning and end of the campaign life,alternating deep and shallow sets of thermocouples could be installedaround the blast furnace.

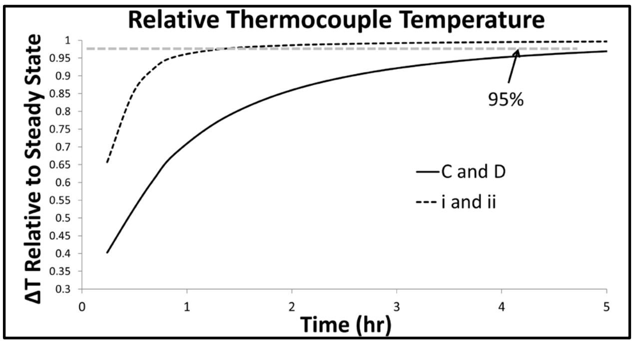

Fig. 8: Transient response of thermocouple pairs

6CONCLUSION

AU-E measurement provides 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 / reliable due to instrument error or plant data logging practice. Heat transfer assessments can be used to identify periods of refractory wear and a reasonable estimate of the extent of the wear. The combination of the two methods provides more accuracy in assessing the hearth wall and bottom conditions.The results are then 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 down-time.

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 multiple days before a new equilibrium is reached. Therefore, a temporary loss of skull may not be identified by thermocouple temperatures if they are 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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