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NON-DESTRUCTIVE TESTING (NDT) AND INSPECTION OF THE BLAST FURNACE REFRACTORY LINING BY STRESS WAVE PROPAGATION TECHNIQUE

Abstract

Generally speaking, a blast furnace is the main equipment in Ironmaking and the campaign life of a blast furnace depends on its remaining hearth refractory lining [1]. The Acousto Ultrasonic-Echo (AU-E) is a stress wave propagation technique that uses time and frequency data analysis to determine coarse-grained material thicknesses, such as refractory and stave materials in operating blast furnaces. A mechanical impact on the surface of the structure (via a hammer or a mechanical impactor) generates a stress pulse, propagating into the furnace layers. The wave is partially reflected by the change in refractory layer properties, but the main pulse propagates through the solid refractory layers until its energy dissipates. The signal is mainly reflected by the refractory/molten metal interface, or alternatively by the build up/air or molten metal interfaces that are formed between internal layers or at external boundaries. In this paper, we describe the AU-E technique in details and demonstrate a few results that are indicative of the technique reliability and accuracy.

Keywords: non-destructive testing (NDT), acousto ultrasonic-echo (AU-E), blast furnace inspection, refractory wear, hearth refractory profile, taphole inspection, cracks and discontinuities in refractory lining

Background

The Acousto Ultrasonic-Echo (AU-E) technique was developed in late 1990s in Canada. The main motivation behind the development of AU-E was lack of accurate NDT techniques to determine the quality and quantity of the refractory lining in an operating furnace. The main challenge was to select a methodology to be able to measure refractory thicknesses from outside the vessel and without disturbing the operation and the production line. Various methodologies were reviewed.

Available Methods for Determining Refractory Lining Thickness in Blast Furnaces

The most common technique for determining the residual refractory thickness in a furnace is the use of mathematical models based on the thermocouples and the process-related furnace temperature values [2]. The accuracy and predictability of the finite element analysis (FEA) and other numerical methods for computational fluid dynamics (CFD) and heat transfer models are based on the accuracy of the assumptions, accuracy of the temperature data, homogeneity and accuracy of the thermal properties in the refractory, skull and the inner hot face. The thickness profiles generated by the mathematical models are necessary and common; however, relaying entirely on temperatures and using homogeneous parameters for heterogeneous media always result in errors.

Another recently developed technique is the application of ultrasonic waves in determining the remaining refractory lining. For ultrasonic waves the frequency of the signal is above 20 kHz which means the wavelength of the signals are small and the frequency of the signal is usually fixed at the transmission frequency. For the ultrasonic waves, due to high frequencies, the penetration depth is small. In addition, because of heterogeneous properties of the refractory materials, temperature, and the multi-layered vessel cross section, the ultrasonic waves attenuate rapidly. At best it requires a very strong energy source or a high energy pulser in the range of 2,000 to 10,000 volts. Another very important issue with the ultrasonic wave is that the wave path "bends" due to high temperatures. This means that the reflections from the refractory hot faces will not echo directly back to the source. This deviation angle depends on the signal frequency, medium material properties, and temperature of the hot face.

The differences between ultrasonic and acousto ultrasonic-echo (AU-E) techniques are the followings:

- Impact generated AU-E pulses are high energy in comparison to piezoelectric generated ultrasonic pulses.
- AU-E signals are broadband but ultrasonic signals are narrowband.
- In AU-E technique multiple reflections from the interfaces help determining the refractory parameters but in ultrasonic ringing and multiple echoes are considered noise.
- The low frequency displacement AU-E signals do not bend due to the heat but the ultrasonic waves do bend.

A combination of thermal modeling based on the furnace temperature readings and a stress wave propagation technique would be the most complete way of monitoring refractory lining condition for an operating blast furnace.

Acousto Ultrasonic-Echo (AU-E) Technique

The AU-E equipment includes an impactor, a receiver and a data acquisition system. A receiver placed beside the impact area detects surface displacements caused by reflections from internal and external interfaces. The signals are analyzed both in time and frequency domain, where the controlling factors include changes in thickness, temperature, density, elasticity, dimensions, and wave speed.

With this methodology, the principal stress wave captured and analyzed for quality assessment is the Primary wave (P-wave), or the compressive wave. The compressive wave speed is affected by the density, thermal gradients, shape and dimension factors, and elastic properties. A sample graph showing the stress wave velocity vs. temperature correlation for a carbon brick used in one of the inspected blast furnaces is shown in. The AU-E technique utilizes the temperature correction factor in order to assure the high accuracy of the thickness computations.

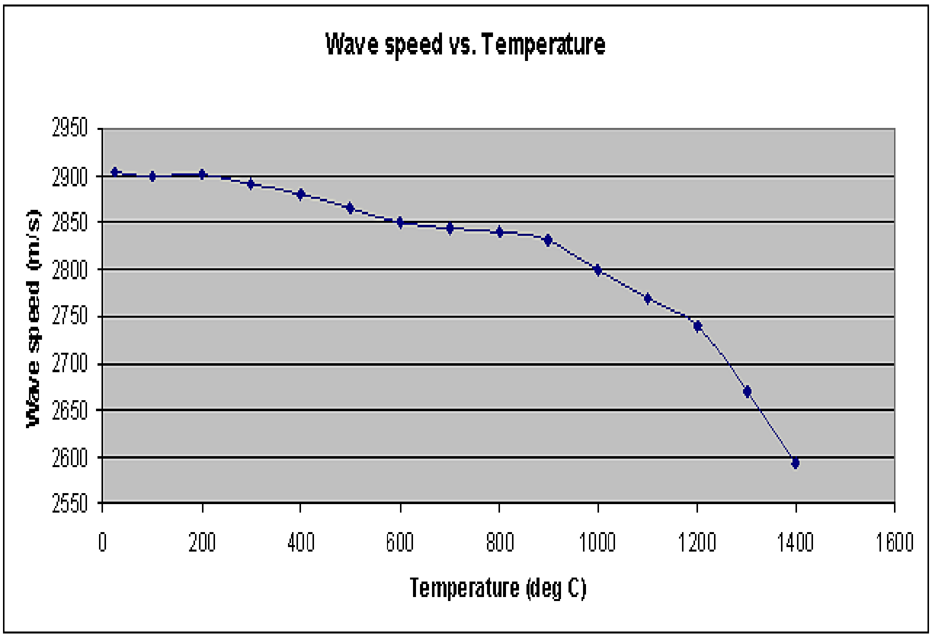


Figure 1. Stress wave velocity vs. temperature – sample data for carbon brick

A drastic change in density and/or in elastic properties of the material will result in partial or total reflection of the wave. In addition, stress free zones, such as cracks and discontinuities, will result in partial or full reflections.

The resonance of the P-wave arrivals to the surface causes a periodic spectrum that can be best viewed by converting the time-domain spectrum to a frequency domain using the fast Fourier transform (FFT) technique. Equation 1 is the fundamental AU-E equation, where the T is the thickness and f_p is the frequency of the P-wave reflecting between the two interfaces.

Equation 1: Fundamental AU-E equation

$$T = \frac{\alpha \beta V_P}{2 f_P}$$

In the above equation, α is the thermal correction for the P-wave speed and the β factor is the shape factor correction for the P-wave speed. Equation 1 is correct when the refractory material is limited to a single brick or single layer. For multilayer refractory lining, the resonance frequency of the P-wave is a result of the total (sum) of responses from each layer of the refractory lining.

Refractory Oxidation or Brittle Zone Detection

Once the signals are reflected from various interfaces, the wave speed, shape, and thermal corrections can be used to determine the thickness of the refractory layer or distance of the interfaces to the source. When there are discontinuities or multiple instances of cracking, the signals tend to reflect at higher frequencies and at a broader bandwidth. The peak frequencies can then be used to determine the position of any cracks and discontinuities. It has to be noted that the large size cracks or discontinuities cause full reflection of the stress wave signals. That means that beyond the discontinuity or the gap the wave can not progress into the wall and the system cannot determine the full thickness of the refractory lining. Two examples, showing a minor anomaly (causing a partial pulse reflection and allowing thickness/build-up computation) and a severe anomaly (causing a full pulse reflection) are shown in Figure . These so called "blind zones" are important to be identified because in a blast furnace where the gaps and cracks between the refractory layers are so large that do not allow for the stress wave to travel, the same gaps also cause the problem of not allowing the refractory cooling take place because the cooling action is disrupted by the gaps and cracks. These gaps and discontinuities commonly form on the sidewalls and could not be identified by the thermocouples and the mathematical models, however stress waves are very sensitive to their presence.

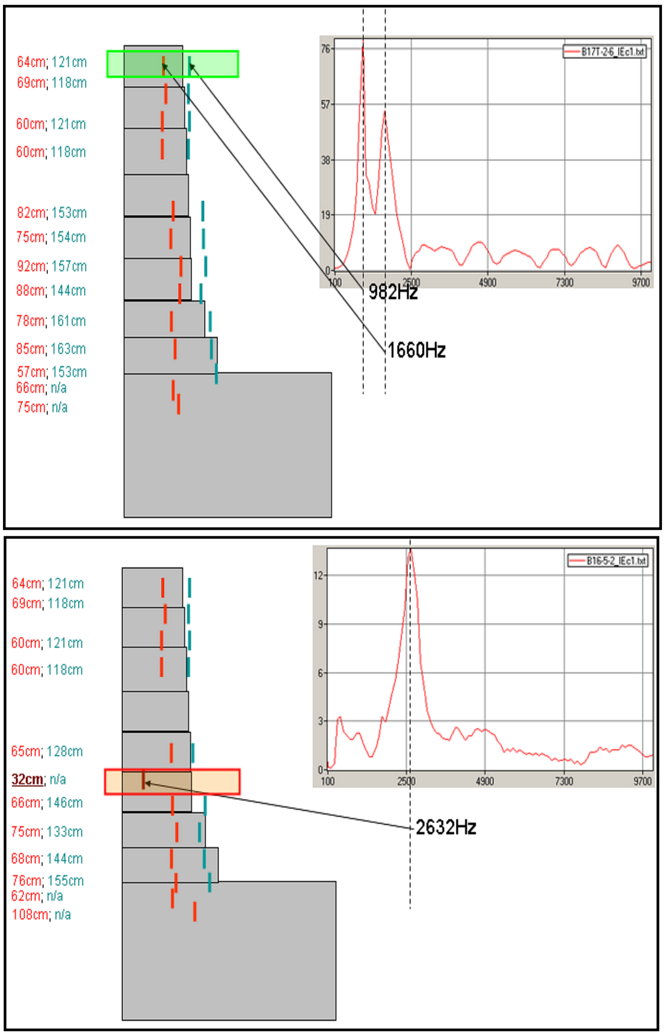


Figure 2. Sample frequency peaks for the AU-E analysis.
LEFT – representing a minor anomaly and build-up;
RIGHT – representing a severe anomaly causing the full pulse reflection

The method for detecting oxidation and brittle zone in the carbon or graphite lining is the same way as detecting cracks and gaps; however, in many instances the interpretation differs from the above because the degree of oxidation has a significant influence on the reflected signals. The time-domain signals will show high frequency components and very high energy losses as the higher degree of oxidation results in proportionally higher signal attenuation. None the less, the best indicator of oxidation remains the evaluation of the wave speed. With advanced oxidation refractory, wave speeds will be dramatically lower than with normal brick; therefore, when sending signals into the refractory lining, the presence of oxidation or brittle zone can be determined where the lining is measuring thicker than what it is supposed to be. If the oxidation materials result in complete separation of the carbon and graphite, the brittle zone behaves as a discontinuity and can be detected readily by the AU-E signals.

Sidewall Refractory Wear

Refractory wear is identified as sections of the refractory that are either de-bounded (broken away) or extensively "impregnated" by molten metal. Impregnation occurs when the molten material infiltrates into the refractory matrix. In both cases, for the stress wave signals the refractory material properties changing severely; therefore, the signals are extensively reflected at their interface boundary. This boundary is considered the refractory thickness [3].

The thickness/build-up computations for the individual test points are combined in refractory thickness profiles. A set of cross-sectional drawings is generated for every tested furnace. The measurement results are overlaid on the original/design cross-sections. Sample illustrations showing the remaining thicknesses, anomalies and build-up for two adjacent cross-sections of a blast furnace are provided in

Figure .

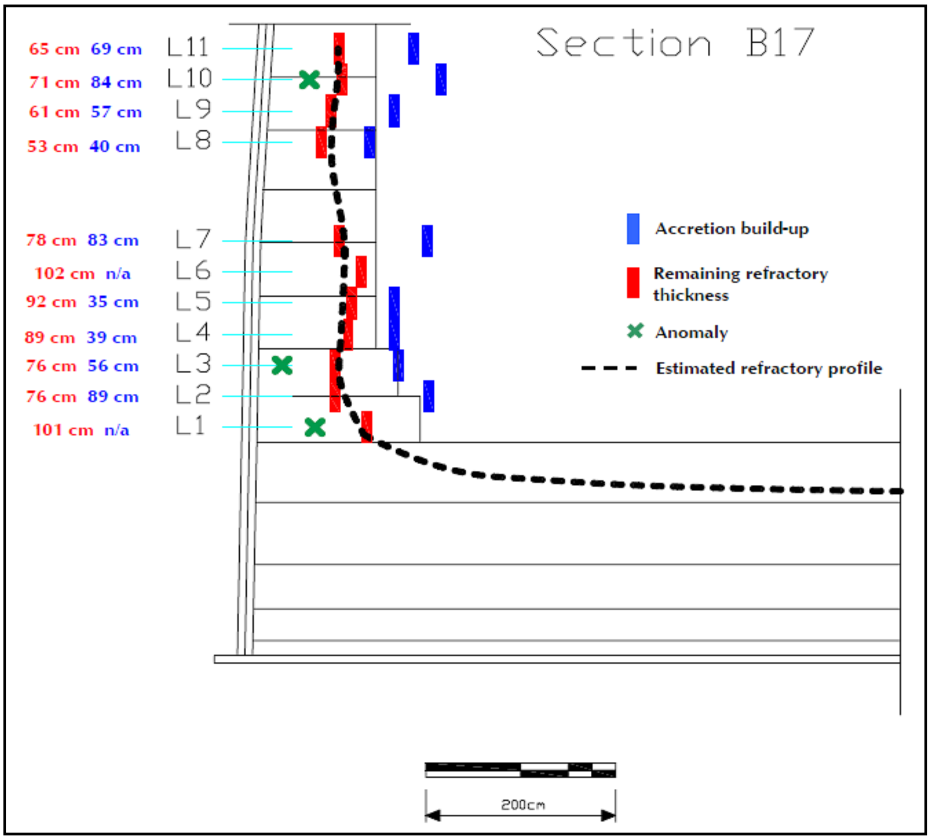
The dashed lines shown on the drawings in

Figure illustrate the remaining thickness of the sound refractory. The estimate of the accretion build-up is also shown. However, build-up thickness computation is a very complex task, and high accuracy of such calculation cannot always be guaranteed. Unlike for the bricks, the build-up samples are typically not accessible for calibration. Due to that fact, the actual stress wave velocity for this material cannot be determined. It can, however, be estimated based on the material properties and the process-related operational data for the tested furnace. Such build-up thickness estimate, even with all the accuracy limitations, still provides valuable information for the blast furnace operators [4].

The results for the individual cross-sections are later plotted on a mesh representing the developed shell of the blast furnace (see

Figure). The point measurements are extrapolated over the tested area. Typically, the percentage of the refractory wear is shown in order to identify the patterns of deterioration. In

Figure below, the highest brick wear was detected for the section labelled as B18, which also exhibited high temperature readings.



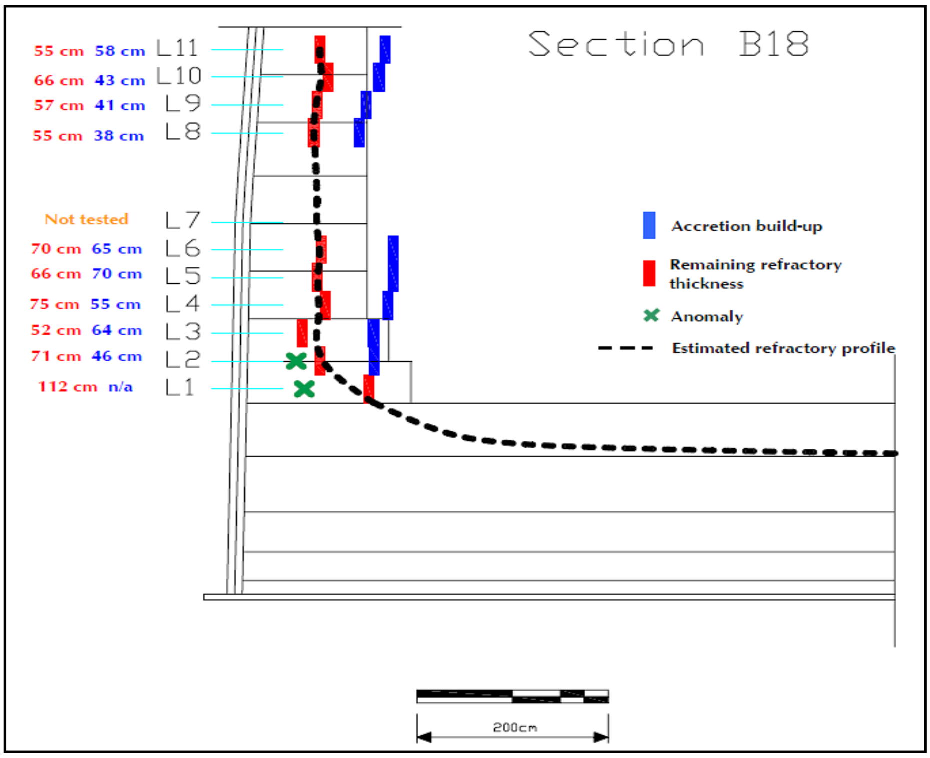


Figure 3. AU-E measurement/computation results overlaid on the design cross-sections

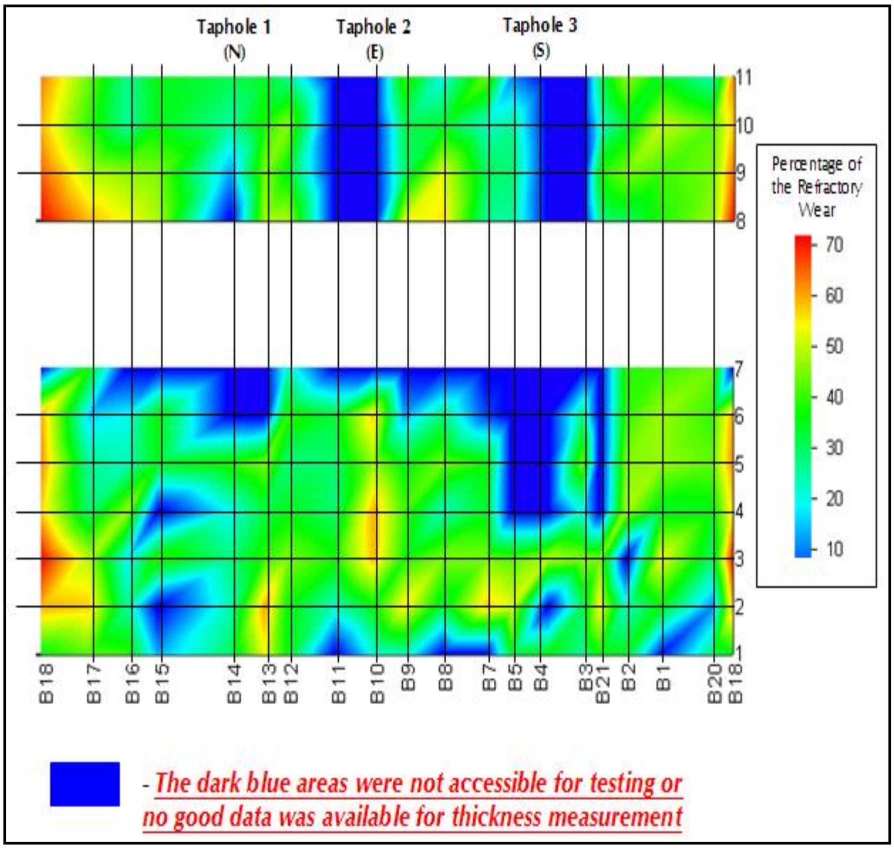


Figure 4. Percentage of the refractory wear for a blast furnace presented on a developed shell

Closing Remarks

The Acousto Ultrasonic – Echo technique has proven to be a reliable and accurate method for blast furnace refractory condition monitoring. The following observations and conclusions must be emphasized based on the results of numerous blast furnace inspections:

- AU-E provides accurate results for the refractory thickness/wear computation, based on the measurements taken on a dense grid of test points. Results from individual test locations are used to generate the cross-sectional refractory profiles, and eventually, to build a 3-dimansional wear/thickness model.
- The thickness computations are based on physical measurements at multiple test locations (typically, over 300 test points per furnace), as opposed to numerical modeling relying on temperature readings from a very limited number of thermocouples.
- Significant anomalies and discontinuities, such as cracks in bricks or development of brittle zone, are immediately identified, allowing for better maintenance scheduling and safer operations of blast furnaces.
- Detection of build-up and estimation of its thickness provides means for blast furnace process optimization that can extend the campaign life.
- The AU-E results were validated through core drilling. They showed very good correlation with the physical measurements, typically with higher accuracy than provided by numerical modeling [5].

- The periodical inspection of the blast furnace refractory using the AU-E technique not only provides “snapshot” image of the current condition, but also shows the deterioration rate and critical locations vulnerable to wear. Such results are frequently used for maintenance scheduling and process improvement.

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ОСОБЕННОСТИ ДЕСУЛЬФУРАЦИИ ЖЕЛЕЗОРУДНЫХ ОКАТЫШЕЙ ИЗ ВЫСОКОСЕРНИСТЫХ КОНЦЕНТРАТОВ В ПЕРЕСЫПАЮЩЕМСЯ СЛОЕ

Аннотация

Проведены лабораторные исследования процесса десульфурации окатышей из высокосернистого концентрата (содержание серы более 1 %) в пересыпающемся слое. Установлено, что наиболее мощным фактором, влияющим на полноту десульфурации служит температура обжига.