Non-Destructive Testing (NDT) and Monitoring of Refractory Lining in Operating Furnaces

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ABSTRACT

The refractory lining in a smelting furnace is crucial to providing structural integrity to the furnace and protecting the furnace are designed to withstand extreme mechanical, chemical and thermal stresses; however, soon after the start-up of a furnace, the refractory lining inevitably suffers from wear and deterioration. The measurement and evaluation of the refractory lining of smelting furnaces is crucial to continue operation. However, due to the nature of smelting furnaces, it is nearly impossible to drill into the lining while the furnace is in operation and directly evaluate the refractory thickness and condition. Due to this limitation and industry demand, several non-destructive testing (NDT) methods were developed. These NDT techniques can indirectly measure refractory lining thickness and can evaluate refractory quality by determining if any chemical changes, hydrations, cracking, oxidation or metal impregnation have occurred within the refractory. The accuracy of these indirect NDT methods relies largely on the quality and homogeneity of the refractory bricks in the lining. In this paper, the available furnace refractory lining NDT and monitoring techniques will be reviewed and discussed.

INTRODUCTION

Every furnace shutdown and start-up causes expansions and contractions in the lining and inevitably further deterioration of the lining. Wear and deterioration of the lining continues during the operation of the smelting furnace, with varying degrees of wear depending on particular smelting processes (ex: binding system arrangements, thermal conditions, refractory lining cooling). Often the reason for furnace campaign termination is the partial failure of the refractory lining. Therefore, for the purpose of furnace health monitoring, the thickness and integrity of the refractory lining must be known at all times.

ONLINE FURNACE MEASUREMENT TECHNIQUES

There are several methods and techniques that are used while the furnace is in operation to measure refractory quality and thickness. These techniques are known as “indirect” methods. Different indirect techniques have particular measurement frequencies which can range from yearly inspections to continuous monitoring. Indirect techniques require certain assumption(s) in their calculations and measurements which can result in discrepancies and errors if the data analysis is not done correctly. In addition, the selection and implementation of the instrumentation and method must be made based on the required scope and particular deliverables.

THERMO-MODELLING ESTIMATES

Numerous mathematical models have been developed based on thermal measurements to estimate the remaining refractory thickness in a furnace. The specialized models have been developed for each application, such as blast furnaces and pyrometallurgical furnaces, and the respective operational components, such as “elephant foot” and “mushroom effects” in blast furnaces and “electrode positions” and “freeze line” for electric arc furnaces [1 and 2]. In modern furnaces, the walls and the hearth have embedded thermocouples to monitor the temperatures of the furnace walls. By using the temperature readings of the thermocouples, the heat fluxes in the refractory lining can be calculated. These heat flux calculations are used in the computational model(s), based on heat transfer and energy conservation to determine the remaining refractory and accretion/build-up thicknesses. The models are only as accurate as the accuracy of the inputs, assumptions and coefficients. Also the models rely heavily on the quantity of the installed thermocouples and their distribution in the furnace structure.

INFRARED (IR) THERMOGRAPHY

The infrared (IR) thermography has traditionally been the most common NDT technique used for determining hotspots and troubled areas. This technique uses IR cameras which provide a thermal images showing the surface temperatures of an object on a color scale. Temperature differences located on the surface may be related to loss of refractory thickness and/or subsurface defects which create heat flux variations.

However, there are limitations to the IR technique. As mentioned previously, smelting furnaces have a steel shell which oxidizes over time. The rusting of the steel shell affects the surface emissivity of the surface which results in inaccuracies in the IR thermography measurements [3]. In addition, near surface gaps, cracks and voids will affect the results. Nearby heat sources and reflections from nearby objects also affect the IR thermography data and might be misleading in interpretations [4].

Due to the mentioned limitations, IR thermography is mainly used for rough estimates and the thermal images must be carefully collected under the same set of conditions for comparison purposes. However, if the data is collected carefully and all the required parameters such as material emissivity, air temperature and moisture are collected carefully and precisely, accurate refractory thickness measurements can be achieved in single layered hollow cylindrical vessels such as converters and reactors [5].

RADIOACTIVE ISOTOPE TRACERS

Radioactive tracers were used for determining refractory thickness in converters, glass furnaces and blast furnaces since the 1960s. Most of the published literature refers to the use of tracers in blast furnaces [3], in particular the 40La, 192Ir and 60Co isotopes, for lining thickness measurements. This method involves introducing radioactive isotope tracers with short half-lives to the blast furnace at the top of the furnace. As the tracer moves downward with the burden, the receiver or isotope’s tracer counter counts the radiation that passes through the build-up, refractory, staves and the shell. Theoretically, where quality of the refractory is homogeneous throughout the furnace and the shell thickness is uniform, the increase in the radiation count would indicate a thinner and more worn refractory lining. However, blast furnace linings are not uniform and several types of refractories with different material properties are utilized in the linings. In addition, the presence of accretion/build-up and/or cooling staves and plates adds to the complexity of the lining. With the radioactive, any type of chemically attacked refractories or cracks won’t be noticed. Therefore, the fluctuation in radiation counts do not necessarily indicate changes in refractory thickness. Since late 1980s, the tracer method has not been used for refractory thickness measurements due to complexities involved with the data interpretation, and the health and safety risks for the operators due to handling toxic and hazardous materials.

ELECTROMAGNETIC (EM) / MICROWAVE TECHNIQUES

Electromagnetic (EM) techniques are effective for assessing refractory when there is no metal “shell” or other conductive structures which cause the EM signals to reflect or distorted. A change in dielectric constant or conductivity results in the reflection and refraction of EM waves back from an interface [6]. This property enables EM systems to be used for measuring refractory lining thickness.

There are several limitations to using EM techniques to measure refractory lining in smelting furnaces. Most furnaces have external steel shells which prevent the propagation of EM waves through the steel shell and into the lining. In addition, the presence of support and grillage beams, or any metallic object, in close vicinity of the EM system antenna will cause signal phase distraction and which may result in false signal interpretations. EM signals are not very sensitive to refractory/air interfaces, therefore voids and gaps cannot be detected in the lining. The air gaps between the refractories cause signal attenuation and reduce the signal-to-noise ratio. The refractory/metal interface will cause EM waveform reflections, hence metal impregnation into the brick, metal penetration in between the lining courses and presence of accretion or build-up will affect the accuracies. Also if metal penetration between brick layers is present, then the EM waves will not be able to propagate beyond this interface. In addition, the dielectric constant of the refractories changes at high temperature which requires a correction factor to be used in the calculations.

In certain cases, EM systems can be used where part of the furnace lining is exposed and antennas can be placed directly against the refractory wall or hearth. In particular, microwave and low frequency radar systems, such as GPR, have successfully been used for determining refractory brick thickness prior to installation and on offline furnaces. GPR is commonly used in non-destructive testing of concrete and masonry structures, where it is used to detect multiple qualities including the thickness of the structure, the location of voids or inclusions and the location of rebar in reinforced structures. The best frequency range for measuring refractory linings is between 500 MHz to 1 GHz, which matches the typical frequency range of commercial short-pulse radars. GPR is commonly used in non-destructive testing of concrete and masonry structures. For these standard applications it produces multiple results, including thickness of the structure, location of voids or inclusions, and location of rebar in reinforced structures. The authors of this paper have utilized GPR systems to measure refractory thickness in electric furnaces. In several furnaces, high frequency antenna between 900 MHz-500 MHz were able to measure the brick wall and roof thickness. The measurements were done from outside where there was no shell and the refractory cold face was exposed.

In addition to short pulse radar systems such as GPR, Frequency Modulated Continuous-Wave Radar (FM-CW), which uses a triangular waveform to modulate the frequency of an oscillator, was also used in laboratory condition for detection of refractory wear in glass furnaces with limited success [7].

ULTRASONIC

Ultrasonic testing refers to the application of the sound wave or stress wave analysis, at frequencies greater than 20 kHz, for material or structural evaluation. Low frequency “Ultrasonic Pulse Velocity” (UPV) systems such as PUNDIT and V-Meter have been used to determine refractory quality since the mid-80s. Using the UPV systems, a refractory with known thickness is placed between a transmitting and receiving transducer which are at opposite ends of the refractory sample. A low frequency “Ultrasonic Through Transmission” (UTT) system with frequencies between 20 to 200 kHz is used to determine time of flight between the transmitter and receiver. Generally, high ultrasonic wave speed indicates refractory materials with low porosity, high density and high modulus of elasticity. “Ultrasonic Pulse-Echo” (UPE) systems are required to measure refractory thickness on an operating furnace. In UPE systems, the transmitting and receiving transducers are placed on the same surface and the distance between the transducers should be minimal. Parker et al. [8] demonstrated that the refractory/molten metal interface creates a distinguishable reflection surface using UPE systems since the acoustic impedance in liquid is typically 13-15% less than for a solid refractory or accretion material. Thus, at the refractory/molten metal interface, at least 10% of the waves are reflected back. Parker and his co-authors demonstrated that a large amount of ultrasonic energy attenuates within the solid refractory because of temperature and porosity. A decrease in the amplitude of reflected ultrasonic signals was noted as the sample was heated to higher temperatures. Temperature also affects the travel path of an ultrasonic waveform in solid [9]. As the temperature increases the longitudinal or P-wave path widens which results in higher attenuation and a change in the reflection angle. For these reasons, ultrasonic systems are typically not feasible options for measuring refractory wear in smelting furnaces.

An ultrasonic system with a “sweep frequency” pulse generator and broadband transducers was developed by the authors in 2012 to determine stave thicknesses in blast furnaces. This Low Frequency Pulse Ultrasonic (LFPU) is a pulse-echo system that is capable of measuring stave thicknesses with a 2 mm precession [10]. The LFPU system is different from conventional ultrasonic systems which use single frequency transducers with fixed and narrow bandwidths. The multi-frequency ultrasonic pulses can travel into different layers of a blast furnace wall and can measure accretion and refractory at the tip of the stave. In addition to measuring copper and cast iron stave thicknesses, LFPU was used to measure refractory thickness between the stave fins. It is believed that LFPU can successfully measure refractory thicknesses of up to 500 mm thickness with a degree of high accuracy. It should be noted that if there are no cooling blocks in contact with the thin refractory, a thermal correction factor must be calculated and used in the thickness calculations otherwise the thickness measurements will be inaccurate.

Since the mid-1990s, ultrasonic tomography has been used to determine refractory thickness and quality in blast furnaces [11]. Ultrasonic tomography is widely used in the medical profession and refers to imaging by sections or sectioning, through the use of penetrating ultrasonic waves. For the application of refractory measurement, an array of low frequency ultrasonic transmitters and receivers are installed on the circumference of the cylindrical shaped blast furnace. The transducers transmit and receive ultrasonic signals in a sequential way. The measurements are repeated in three to four different locations around the furnace. The received ultrasonic wave parameters in directional, tangential and radial directions are used to recreate the remaining thickness “image shadow”. The “image shadow” is developed based on mathematical modeling and correlations between the arriving ultrasonic waves at the various transducers and the known qualities of the blast furnace layers. The key factor is the accuracy of the base mathematical model and the acoustic impedances between the lining layers and the lining and the molten materials. There are, however, numerous challenges and concerns with this technique when applied on an operating furnace including: the accuracy of the base computational model, the high frequency of the ultrasonic wave (above 20 kHz), the high rate of signal attenuation because of temperature and material porosity and the complex signal pathways through the refractory lining.

ACOUSTO ULTRASONIC-ECHO (AU-E)

The Acousto Ultrasonic-Echo (AU-E) technique was developed in the late 1990s based on the same principles governing the impact-echo (IE) technique [12], a concrete NDT evaluation method, with additional modifications, to account for the effects of extreme temperature on the wave propagation, multi-layer lining with a different acoustic impedance for each layer and furnace shape and dimensional effects. AU-E is a patented technology that has been commercially used by the authors for refractory thickness and quality evaluation since 1998.

AU-E is a stress wave propagation technique that uses time and frequency data analysis to determine refractory thickness and detect anomalies such as cracks, gaps or metal penetration within the refractory lining. During the measurement, a mechanical impact on the surface of the structure (via a hammer or a mechanical impactor) generates a stress pulse, which propagates into the refractory layers. The wave is partially reflected by the change in material properties of each layer, but it also propagates through the solid refractory layers all the way up to the interface at the end of the brick. The compressive waves (or P-waves) are received by a transducer and the signals are analyzed for quality and thickness assessment of the refractory.

The AU-E technique uses the apparent wave speed (the average wave speed in a three dimensional geometric space) in calculations instead of the actual P-wave speed. The P-wave speed in each layer is affected by the density, thermal gradients, shape factor and elastic properties of brick. The AU-E technique uses correction factors to account for the apparent speed in each layer. One such correction factor is the thermal factor, α, which is calculated based on refractory dynamic Young's modulus of elasticity under service conditions compared to the dynamic Young's modulus at room temperature.

Another correction factor, the shape factor β, accounts for reduction in wave velocity due to geometry of the structures the waves are travelling in. The apparent wave speed offset is due to excitation of structure's natural frequencies by the impact force. The shape factor value depends on the cross section dimensions of the testing area. For most furnaces where lateral dimensions are at least six times the thickness of the lining, β is 0.96 [13].

In addition to understanding the mechanism of the stress wave measurements, an important factor for a successful AU-E inspection is the utilization of the right tools. A broadband vertical displacement transducer of a desirable frequency response range was designed with the ability to function at high temperatures and in wet environments. For pulse generation, impactors were selected with specific spherical tip diameters, capable of generating a specific range of frequencies. The data acquisition system was designed to be a military grade, water and dust resistant system which was able to withstand high and low temperatures between -50 °C to 90 °C.

CALIBRATION

The standard AU-E procedure involves calibration prior to the data collection. The calibration involves determining the apparent P-wave speed for each brick type, $(V_p)_i$, with representative brick samples at room temperature. The wave speed measurements must be carried out on all the materials that the wave is passing through to ensure the highest levels of accuracy. The α factor can be calculated either experimentally, by heating brick samples and measuring the wave speeds at the desired temperatures, or theoretically, by the brick elastic and thermal properties. For the β factor, the value can be calculated once the dimensions of the testing area are available. After the calibration, a mathematical model is created to help the AU-E specialist with the necessary hardware and software equipment settings for the AU-E data collection.

THICKNESS MEASUREMENTS AND REFRACTORY WEAR

The AU-E data is collected in the time domain and, when displayed, it is extremely complex, containing numerous periodic signals resulting from multiple reflections, diffractions, refractions from body and surface waves. In the frequency domain the results are better defined, as the periodic signals are identified by their center frequencies. However, there are still many different elements that can cause misinterpretation. The results of the AU-E technique can show other refractory conditions which appear, at first glance, as the detected remaining refractory thickness; namely, metal impregnated refractory and accretion or build-up. When refractory is impregnated by metal, the impregnated portion has a significant reduction in elastic property compare to the original refractory. AU-E signals will be reflected from the impregnation boundary, which can be mistaken for the remaining refractory thickness. When accretion or build-up is formed on the hearth, the build-up/molten material interface can be misinterpreted as the remaining refractory thickness, while the build-up/refractory interface can be misinterpreted as a crack or impregnation boundary. Proper interpretation of AU-E signals can be aided by a good understanding of the furnace process and operating conditions. Like other tasks which require judgment, the AU-E technique requires the experience of an AU-E specialist.

DETECTION OF ANOMALIES

The AU-E technique defines an anomaly as a clear signal reflection from within the refractory lining whose source cannot be known with certainty. Anomalies could be material discontinuities, cracks, voids, metal penetration, hydration or a combination of these features. Discontinuities, cracks, voids, or interfaces of different materials, typically result in multiple reflections at higher frequencies compared to the low frequency reflection from the full refractory thickness. When significant gaps/cracks are present in the bricks, the waves generated from the impact may not transmit through the entire thickness of the brick and instead seem to reflect from a thinner region closer to the cold face. As such, careful attention is required to identify the difference between a significant crack and a worn refractory lining.

DETECTION OF REFRACTORY CHEMICAL CHANGES SUCH AS HYDRATION, CARBONIZATION, AND OXIDATION

The apparent P-wave speed of refractory is dramatically lower when it is hydrated/carbonized or oxidized; therefore, greater than expected refractory thickness is measured in areas of hydrated/carbonized or oxidized refractory. The magnitude of the P-wave speed decrease depends on the severity of material changes within the lining. If the area of the chemical change is small in relation to the length and geometry of the lining, the AU-E signals may not be affected so the change in refractory quality may not be detected. On the other hand, if the chemical effects are extensive in geometry and material properties in relation to the lining, AU-E signals will readily detect the defected area. Determining the severity of refractory chemical changes is difficult. The severity of the chemical changes to the bricks depends on the volume of the external agent (water in the case of hydration), time of exposure, temperature and how favorable the conditions are for the chemical change. More data is needed at this time to identify the different stages of refractory chemical changes and to determine the severity of the defected area.

METAL PENETRATION

Metal penetration into the refractory can also result in “thicker than normal” measured refractory lining sections. AU-E cannot identify metal penetration within the refractory lining when the penetration is “smaller than signals half wavelength” which, in this case, is less than 50 mm. When metal penetration is too small for AU-E to detect as a separate interface, the additional metal thickness will be reported as part of the lining resulting in a “thicker than normal” reading. This problem is further complicated if the metal penetration occurred before the AU-E calibration. In these cases, it is difficult to identify the metal penetration and the full thickness of the refractory could be misinterpreted as the build-up. One of the only identifiers from the AU-E data is the “noisy” characteristics of echoes from metal penetration in comparison to the less “noisy” signals from the refractory full thickness. However, “noisy” signals could also be interpreted as cracked or chemically changed refractory and might not be an indication of metal penetration.

ACCURACY OF AU-E MEASUREMENTS

The accuracy of AU-E measurements is directly related to the quality and consistency of the refractories used in construction of the furnace. Consider the following example: AU-E is used to measure the thicknesses of two refractory bricks of the same type; if two refractory bricks are assumed to have the same properties, they will thus be assumed to have the same P-wave speed; if in fact one of the P-wave speeds of the bricks is 10% higher than normal, than the error of that thickness measurement will be 10%. As a result, the higher the quality and consistency of the refractories, particularly in terms of mechanical properties, the better the accuracy of the AU-E measurements will be.

The effect of refractory consistency can be mitigated in part by having several refractory samples to calibrate the AU-E system on. As discussed previously, measuring the apparent P-wave speeds in the samples and directly computing the shape and thermal correction factors produces more accurate measurements. In general, based on numerous verifications, the accuracy of the AU-E measurements is between 4-7% of the full refractory thickness and/or anomaly position measurements. The accuracy of the accretion or build-up thickness measurements is 15% or below due to the greater uncertainty in the P-wave speed of accretion or build-up.

CONCLUSIONS

One of the primary reasons for the termination of a smelting furnace’s campaign life is refractory wear and the corresponding loss of the furnace’s capability to operate safely. Due to advances in technology and equipment since mid-1960s, various tools have been developed to help furnace operators to determine the condition of the refractory lining. In late 1990’s, the AU-E technique was developed based on stress wave propagation principals. Periodic AU-E inspection of furnaces have been adopted by operators of all different types of furnaces worldwide as part of their maintenance plans. AU-E results have successfully identified methods to extend furnace lining campaign lives without compromising safety.

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