Abstract. Smelting furnaces are structures designed to produce metal from raw ore. Furnaces are constructed and operated in a way to withstand harsh thermal, mechanical, and chemical conditions. Furnaces are lined by refractory bricks or castables to protect the structure against the harsh operational environment. With time, refractory linings in smelting furnaces undergo deterioration and wear. The deterioration is mainly caused by thermal stresses and chemical attacks, resulting in loss of heat-transfer and load-bearing capabilities. Failure of the lining is dangerous and can affect the structural integrity of the furnace. The degree and mechanism of deterioration depends on many different factors. To examine and monitor smelting furnace integrity, a number of non-destructive testing (NDT) techniques have been developed by the Hatch NDT Group. NDT and monitoring of the refractory lining leads to better safety, longer service life of the furnaces, controlled maintenance, and increased production. In addition to our refractory inspection techniques, we have utilized acoustic emission (AE) to monitor furnace and taphole structural integrity, fiber optics to tightly monitor the hot face of furnace tapholes and high frequency radar systems to monitor and control feed levels in the furnace. In this paper, we will discuss and share case studies on these and several other NDT and monitoring systems that we have developed in the past 16 years to inspect and monitor operating metallurgical furnaces.

Introduction

In a metallurgical plant, smelting furnaces are the indisputable key equipment that controls the rate of production. Similarly to any other manufacturing and production unit, smelting furnaces are subject to wear and tear over time, and require regular maintenance and occasional repairs. After commissioning a metallurgical plant, the main task is to maintain production, control the costs, and ensure safety. To focus on these three main tasks, the Hatch NDT Group has developed specific NDT and monitoring systems to assist furnace management and operators.
1. Refractory Brick in Furnaces and Process Vessels:

Smelting furnaces and process vessels are lined by refractory brick or refractory castables. Refractory is a composition of materials that are resistant to the heat, and to the chemical and mechanical attacks that occur during the smelting process. The exact composition of the refractory material and its arrangement in a furnace is designed based on the particular smelting process and furnace type. The harsh conditions inside the furnace cause deterioration of the refractory lining almost immediately after furnace start-up. Overtime, the lining wear progresses, in large part due to cycles of maintenance shutdowns and start-ups. Eventually, this wear results in the reduction of the furnace campaign life. Early detection of refractory wear and continuous or periodic monitoring of lining condition are essential tasks that help continuous, safe operation of a furnace.

2. Methods to Measure and Monitor Refractory Lining

Historically, several NDT techniques have been used for inspection and monitoring of smelting furnaces. The most common technique is the use of temperatures and thermal fluxes to determine the remaining lining thickness. To get the refractory temperatures, operators insert thermocouples into the lining at various locations and depths into the lining. Temperatures are collected continuously from the thermocouples. Based on the thermal flux values from the thermocouples and the thermal properties of the refractory materials, the remaining lining thickness is calculated. While this is an essential and useful refractory condition monitoring system, it has some limitations. For example the mathematical models used to calculate the remaining lining thickness are designed based on various assumptions that may be incorrect or inaccurate. Additionally, the number of thermocouples, their distribution and their quality affects the calculations.

Thermal cameras are extensively used for furnace assessments because the cameras are easy to use, reasonably priced, and globally available. Around the furnaces, the main use of a thermal camera is to detect “hot spots” on the vessels. Hot spots can indicate increased refractory wear in particular areas, metal penetration, or other anomalies. For accurate wear detection, infrared cameras can be utilized to determine the refractory loss in single-lined vessels such as a kiln, converter or reactor. However, the complex, multilayered refractory present in furnaces means that shell temperature is not always a good indicator of the lining condition of furnaces. Thus thermal cameras are not capable of effectively monitoring furnace linings.

In the 1960s isotope tracers were used to determine blast furnace refractory lining thicknesses. The isotope tracers were added into the furnace along with the raw material and receivers were placed at each elevation to count the radioactivity given off by the isotopes and determine the remaining refractory thickness. This methodology never gained popularity and interest by operators due to radiation hazards and lack of accuracy.

Despite being in the research phase, an interesting approach is the utilization of electromagnetic (EM) reflection systems for the detection of flaws and refractory thickness measurements. There are several research programs and theses written on this subject. While the topic sounds quite interesting, in reality EM signals are not a practical approach for refractory measurements in metal smelting furnaces for two key reasons. First of all, furnaces have a metallic shell and EM pulses cannot penetrate the metallic shell. Unless the shell is removed, the EM and microwave antennas cannot be used to measure refractory thicknesses. Secondly, metal and slag can penetrate into the refractory lining. This impregnated refractory contains a high level of metal and does not allow the EM and microwave signals to pass into the impregnated brick. Thus it is not possible determine the full refractory thickness and the
signals will reflect from the interface between “good refractory” and “impregnated or infiltrated refractory”.

Among the various NDT and monitoring techniques, the only practical method to use for assessment of the lining in an operating furnace should be based on stress wave propagation techniques. In the following section we introduce two stress wave propagation techniques that are used in the inspection and monitoring of smelting furnaces.

3. Acousto Ultrasonic-Echo (AU-E) Technique for Furnace Inspection

The Acousto Ultrasonic-Echo (AU-E) method was developed in late 1990s based on impact-echo (IE) concrete testing principles. AU-E is a stress wave propagation technique that uses time and frequency data analysis to determine refractory thickness, and to 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, but it also propagates through the solid refractory layers all the way up to brick/brick or brick/gas or brick/molten metal interfaces.

The compressive waves (or P-waves) are received by a sensor / receiver and the signals are analyzed for quality assessment of the refractory. The speed of the P-wave is affected by the density, thermal gradients, shape factor and elastic properties of brick. A drastic change in acoustic and elastic properties of the material will result in partial or total reflection of the waveforms. Thus, signals are reflected by interfaces such as refractory-air, refractory-molten metal interfaces and brick interfaces. In addition, stress free zones, such as cracks and discontinuities will result in partial or full signal reflections.

The AU-E technique accounts for the stress wave velocity change due to shape influence and thermal conditions. The shape factor \( \beta \), accounts for the reduction in wave velocity due to various furnace shapes, such as cylindrical or rectangular. The thermal correction factor, \( \alpha \), is the ratio of the refractory material’s dynamic Young's modulus of elasticity under normal service conditions to the modulus of elasticity at room temperature (Equation 1). If the dynamic modulus of elasticity over a temperature gradient is given as \( E_d(T) \), the temperature correction factor, \( \alpha \) can be calculated as:

\[
\alpha = 1 + \int_0^T \left( \frac{E_d(T) dT}{E_o} \right)
\]

(1)

Where \( E_o \) is the dynamic modulus of elasticity at room temperature.

The governing equation for the AU-E technique is indicated by Equation 2:

\[
T = \left( \frac{\alpha \beta V_p}{2 f_p} \right)
\]

(2)

Where \( f_p \) is the P-wave frequency, \( V_p \) is the propagation speed of P-wave in the material, \( T \) is the thickness or depth of the reflecting surface, \( \alpha \) is the temperature correction factor and \( \beta \) is the shape factor.

For a multilayered section such as a furnace hearth, the thickness of the final refractory layer (\( T_n \)) is calculated based on the following equation:
\[ T_n = \frac{V_p}{2} \sum_{i=1}^{n-1} \frac{2T_i}{(V_p)\alpha_i \beta_i} \]  

For an n-layered structure, the remaining thickness of the nth layer can be calculated by Equation 3, where \( f \) is the resonance frequency for the thickness of the nth layer. Equation 3 can be used to determine the refractory lining thickness on the hot face, considering the P-wave speed \( (V_p) \), the thermal correction \( \alpha_i \), the shape correction factor \( \beta_i \), and the thickness \( T_i \) of the layers prior to the inner most layer are known. Equation 3 assumes that the stress waves generated by a controlled impact source contain sufficient energy to reach the inner most layer of the lining and resonate back and forth between the two faces to create a desirable P-wave thickness frequency.

4. Furnace Monitoring by Acoustic Emission

The utilization of Acoustic Emission (AE) signal detection, analysis and implementation for furnace monitoring is very powerful and underdeveloped. AE testing is a proven method for examining the behaviour of materials deforming under stress \([1]([2])\). An acoustic emission can be defined as a transient stress wave generated by the rapid release of energy within a material. The Hatch NDT Group currently uses AE systems for two main furnace monitoring systems. The first system, Taphole Acoustic Monitoring system (TAM), is used for monitoring furnace tapholes. Tapholes are the area where the hot metal or slag is allowed to flow out of the furnace. The second Hatch AE system (FIMS) monitors the furnace structure. It can help prevent molten metal leaks, as well as help with a variety of process issues.

4.1 Taphole Acoustic Monitoring System (TAM)

The Hatch NDT Group started using AE systems for monitoring inner refractory lining for water cooled tapholes in smelting furnaces nearly ten years ago. The Taphole Acoustic Monitoring system or TAM uses acoustic emissions generated by the flow of molten metal from the tapping channel to recognize relative refractory losses inside the tapping channel. In addition, TAM uses drilling and tapping by the operators to identify damaged and worn refractory inside the tapping channel.

We developed the TAM system to monitor taphole refractory wear because of continuous usage as well as damage due to drilling and lancing. The TAM system works only on copper-cooled tapholes. The key advantages of this system are that it provides immediate detection of stray lances or drills and can be installed on an operating furnace without any taphole retrofitting or complex changes in operations, see Sadri, et al. \([3]\) for details. TAM is based on the AE monitoring principles. The development of TAM was motivated by the need to monitor a particularly vulnerable tapblock that was compromised due to repeated off-center lancing. The system was commissioned in 2007 and was decommissioned in 2012 after the tapblock was replaced. Several events detected by this original TAM system proved its accuracy and value \([4]\).

A typical TAM system consists of a pair of AE sensors mounted on the inlet and outlet of each of the tapblock cooling water pipes. The illustration of this concept is presented in Figure 1, which shows the transmission of the damage-induced stress waves through the various media. The signal is generated by a lance, drill or the flow of metal in the tapping channel. The cooling water pipes act as wave guides for AE propagation. The elastic stress waves propagate through the refractory and copper, and then reach the cooling pipe where
it is picked up by the AE sensors. Further signal processing is done by the TAM software to locate the source of the acoustic emission.

Fig. 1. Schematic diagram of TAM system showing one pair of sensors mounted on the Monel pipe (different color arrows showing the AE transmission in different media)

The TAM system is particularly valuable for detecting the upset conditions caused by off-center drilling or lancing which can rapidly damage a tapblock. These events drastically increase the AE energy released from the tapblock at their locations and thus the events are immediately detectable by the TAM system. The source location algorithm, based on the input from multiple sensors, determines the particular areas of the tapblock where the event(s) originated. In the future, this function of TAM could be used as a guide in automatic drilling and lancing systems. Figure 2 shows a typical screen that would be available to an operator in the field to provide real-time feedback on lancing and drilling actions. This depicts a tapblock, from the perspective of an operator at the cold-face looking into the furnace. The multiple zones represent the brick inserts and the colors indicate the relative severity of the damage (the localized loss of brick thickness). For the illustration shown, the highest damage is reported towards the hot-face of the tapblock, at the bottom-right side. The color-coded damage severity (high, medium or low) relates to the proximity of the molten material to the copper block.

Fig. 2. Visualization of a taphole brick damage detected by TAM
4.2 Furnace Integrity Monitoring System (FIMS)

Furnace Integrity Monitoring System, or FIMS, was developed by the Hatch NDT Group for monitoring the structural integrity of furnace the crucible [5] [6]. Similar to the TAM technique, FIMS uses the principles of the AE monitoring technique. For the FIMS application, AE sensors are mounted on the furnace shell to detect the lining and shell deterioration. The sensors are installed in several rows, forming triangular or rectangular patterns; Figure 3 shows a triangular pattern. This layout allows the entire vessel to be monitored. The highest density of sensors is focused on the most critical zones in the furnace, including the skew bricks and tidal area. Ultimately, the sensor layout for a particular furnace is customized to ensure the optimal monitoring results for that specific design. The start of refractory deterioration, including wear, cracking or opening of the joints is detectable by acoustic emission long before major failure occurs; hence FIMS can be utilized to continuously monitor furnaces and locate defects during furnace operation.

![Fig. 3. Visualization of two rows of sensors forming a triangular pattern for a circular furnace.](image)

The use of multiple sensors enables both the detection and location of deterioration-related signals to be determined. The energy released from a local defect generates elastic wave that propagates through the furnace refractory and shell. The elastic wave is detected by the piezoelectric sensors attached to the shell. The location of a defect is determined by the analysis of the differences in the time-of-arrival (TOA) of the source signal between the various sensors on the furnace shell. The coordinates of the source/defect are instantly computed based on the TOAs and the wave velocity within the material medium.

Two FIMS prototypes were installed in 2008 and 2009 on round electric furnaces in Korea and in South Africa. The purpose of these installations was to validate the feasibility of this concept and to collect initial data. The data acquired by the system installed in South Africa confirmed events leading to a metal leak, as well as the readings from a run-out. This data contributed to the FIMS development at its early stages, and it was utilized to identify patterns and sequences of events that could lead to run-outs.

The latest installation of the FIMS system was performed in the UK on a relatively small DC furnace in 2014. The purpose of the installation was twofold: to provide an early warning before a run-out and to contribute to optimizing the schedule for furnace refractory relines. The latter is achieved by evaluating the refractory conditions in order to avoid premature relining or failures due to refractory deterioration. During the initial three months of monitoring, several events were detected that indicated refractory damage in critical areas.
of the furnace: near the tapholes and near the bottom refractory joint. The latter is considered a severe anomaly as it opens up a pathway for metal penetration. This was also a mode of failure previously observed at this site. The typical pathways of metal penetration, as well as the relevant indication by FIMS, are shown in Figure 4.

![Figure 4](image)

**Fig. 4.** Left: molten metal penetration pathways through a refractory joint. Right: The red dots indicate locations of detected acoustic events. Note that they are clustered at the refractory joint.

Additional information about the refractory conditions based on the FIMS measurements can be derived from the Acoustic Emission activity graph. The Acoustic Emission activity graph shows the cumulative AE events over the time of monitoring. A steep slope on the AE activity graph indicates concerning deterioration and typically occurs shortly following the start-up. This is in part due to the initial refractory growth and movement. A steep slope has also been observed to occur prior to failures due to abrupt changes of the refractory conditions. An example of such AE activity curve and resulting indications of localized events is shown in Figure 5. A large release of energy over a short period of time is often associated with movement of furnace components. Such events appear as clearly distinguishable step changes in the AE activity graph. Often, these events can be traced to specific locations around the furnace to direct operators to the area of concern. This type of information greatly assists operators in assessing the furnace condition and evaluating risk when considering the maintenance requirements and schedule.

![Figure 5](image)

**Fig. 5.** Top: Acoustic Emission activity graph. Bottom: Sample indications by FIMS of localized refractory deterioration. The red dots show the location of the AE event source (the location of the deterioration).
5. Radar Feed Level Monitoring

While refractory wear is a key parameter in furnace health, maintaining appropriate material levels inside the furnace can also have significant benefits. In particular, the ability to maintain an ideal distribution of raw material, or feed, on top of the furnace can help optimize furnace production and reduce maintenance. In electric arc furnaces, proper feed distribution can minimize roof temperatures, increase furnace efficiency, and even minimize the likelihood of dangerous, overpressure events called blowbacks. All of these help to reduce furnace costs, increase profitability, and most importantly increase operator safety. A schematic of an electric arc furnace showing varying feed levels is shown in Figure 6. Hatch has developed a feed level monitoring system based on non-contact radar which is an affordable and accurate measurement system. While several other methods are commonly used for measuring feed level, radar-based measurements offer significant advantages in terms of automation, accuracy, and safety [7].

![Fig. 6. Electric arc furnace showing ideal feed level, as well as the underfed (too little feed) and overfed (too much feed) scenarios.](image)

Non-contact radars are a well-established measurement method and many types and frequencies or radars are commercially available. However, the furnace environment poses many challenges that make it difficult for commercially available radar units to work successfully in a furnace application. Furnaces involve extreme temperatures up to 1800 °C, high levels of dust, and strong electromagnetic interference (EMI), all of which negatively impact the radar unit signal or the unit’s lifespan. To shield the radar units from these harsh conditions, Hatch designed a protective enclosure. This enclosure includes a thermal barrier to protect the radar from excessive dust and radiation, EMI protection, and a robust cooling system.

From 2009 to 2013, a series of trials were performed at an electric furnace in South Africa to validate and optimize the radar measurement system. In 2013, 8 radars were permanently installed based on the success of the initial trials. At this site, the radar units were installed into the roof line of the furnace, as shown in Figure 7. The radar installations offered a significant improvement in feed level control, reducing the standard deviation in the feed thickness from 24 cm down to 6 cm (on a set point of 95 cm). Additionally, the radar units and enclosures proved to be robust and well-suited for the furnace environment. Over
two years later with minimal maintenance, the radar units are still giving reliable and accurate readings [8].

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**Fig. 7.** Roof installation of radar unit on an electric arc furnace for feed level measurements

### 6. Fiber Optic Temperature Monitoring for Tapblocks

For several years Hatch has been installing fibre optic temperature sensors on the copper cooling elements of smelting furnaces to improve monitoring capabilities in critical locations [9][10]. The metal/matte tapblock is a key area to monitor in the furnace as it undergoes severe wear from the molten material repeatedly drained through it. The high wear rate around the tapblock means downtime is necessary to perform refractory repairs. A good understanding of the tapblock condition allows the operation to maximize safety and production; consequently the metal/matte tapblocks have been the focus of this study. Fibre optic technology allows the installation of numerous sensors in locations that are very sensitive to refractory thickness, thereby providing information previously unavailable with traditional sensors.

The key benefits of the fiber optic temperature sensors are the small size of the fiber and the ability to install many sensors along a single fiber optic strand. In addition to the benefits of increased spatial coverage, the small diameter of the fiber allows the sensors to be located such that sensitivity can be optimized. In the case of the tapblock, the fibers are installed across the hot face, on or just below the surface of the copper. Figure 8 shows an example of an installation with two fiber strands (in red) on the copper surface. Sensors spacing is customizable, but 50-100 mm intervals are typical over the regions of interest. This will result in the use of approximately 50 fiber optic sensors per tapblock. The traditional method for monitoring a tapblock would be eight to twelve thermocouples imbedded in the copper; the fibre optic sensors provide a much denser measurement grid. The yellow tubes in Figure 8 show a thermowell/thermocouple arrangement for a typical tapblock.

In certain cases where corrosion on the copper surface is an issue, tubes are cast into the copper tapblock to house the fibre optic sensors. This has clear advantages with respect to protecting the tube from corrosion, but there is some loss in sensitivity with respect to changes in the refractory thickness. The thermal response to changes in the refractory
thickness is highly dependent on the relative distance of the sensor to the hot face and water pipe in the tapblock. More information on the various installation methods is discussed by Braun et al. [11].

**Fig. 8.** Tapblock showing location of thermowells and fiber optic cables

Over the life of the tapblock a general trend towards higher temperatures as the refractory wears is expected. The thermal trends observed during tapping at several facilities are presented in MacRosty et al. [12]. In that paper, analysis of the temperatures at a steady-state condition, approaching a state of continuous tapping, was shown to provide a consistent basis to evaluate refractory condition. Due to different operating practices this approach is only applicable at some facilities. In cases where there is no steady-state reached during tapping, the authors proposed using the dynamic response to determine the refractory thickness.

A key task in relating the measured data to condition requires validating the predictions against actual refractory thickness measurements. A challenge is the few opportunities that are available where it is possible to conduct a measurement survey of the remaining refractory at the hotface of the tapblock. Such opportunities only exist during major shutdowns, which occur on a cycle of between six months to two years depending on the facility. However, the refractory in the tapping channel of the tapblock is replaced on a four to eight week cycle. Examination of the taphole refractory provides an opportunity to relate the condition of the tapblocks to the fibre optic temperature readings in the tapping channel on a more frequent basis than is possible with sensors on the hotface.

Figure 9 shows several months of data from a sensor located in the tapping channel at a facility in South Africa. In this figure, the temperature spikes correspond to the temperature peaks from individual tapping events. The saw-tooth pattern traced out by the peak temperatures during tapping is quite clearly evident and corresponds quite closely to the brick repair schedule. The pattern generally starts out with relatively low peak temperatures (55°C) when the refractory is new and over time it increases, tending towards 65°C just before the next repair. This increase in temperature is consistent with the taphole increasing in size and/or the impregnation of the refractory with more conductive metal. This saw-tooth profile is typical at this facility; however, at another facility there is often a negligible difference in temperature readings before and after a brick repair. It is expected that the brick at that facility is still in good condition when it is replaced. The replacement schedule is often driven by other factors at some sites.
In summary:

- A large number of measurements on a small diameter fiber allows good spatial resolution to be obtained and in locations where it is not possible to install thermocouples. This provides excellent monitoring capability on critical equipment.
- Thermal modelling is valuable for providing context to the measured values to understand the condition of the refractory. The three-dimensional nature of heat transfer through the tapblocks requires sophisticated models to be developed; one-dimensional heat transfer relationships are incapable of capturing the physics for this geometry. In contrast, a furnace wall-lining application can be well approximated with simpler models.
- The accuracy of the prediction can be confounded by the presence of products of corrosion or air gaps that form and modify the overall thermal resistance between the sensor and molten bath. The impact and likelihood of such anomalies should be well understood in order to make a precise assessment of the condition.
- The variable that most significantly impacts the temperature is thickness of the refractory, a fortunate result since this is key variable in evaluating the tapblock condition. Furthermore, as the refractory thickness decreases, its impact on temperature becomes overwhelmingly dominant. At a thickness of 25mm, there is very little uncertainty associated with the prediction. The interested reader is referred to MacRosty et al. [12] for more details on the work conducted to evaluate the sensitivity of factors that impact the measured temperature.

Conclusions

A number of NDT and monitoring systems have been invented and patented by Hatch for industrial furnaces and process vessels. The inspection and monitoring environments of industrial furnaces and process vessels are harsh but it is crucial to effectively inspect and monitor them considering the high safety and economical risks. The NDT and monitoring systems designed by Hatch are developed based on two objectives: 1) inspection and
monitoring of equipment for detecting wear and flaws; 2) monitoring for the optimization of equipment and control. The AU-E, TAM, FIMS and taphole fiber optics systems are uniquely designed to increase safety and protect the assets of producers. The radar system is designed for better feed control and to optimize furnace performance. In tough economic times, where the price of commodities are low, producers need to operate their assets beyond their expected campaign lives, maintain high safety standards, and cut costs by optimizing their equipment. The Hatch NDT and monitoring systems are designed to address these clients’ requirements.

References