Structural Integrity Monitoring of Smelting Furnaces Based on Acoustic Emission Data Acquisition and Analysis

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Abstract
Industrial smelting furnaces are subjected to significant structural changes and deterioration caused by the conditions under which they operate. The current methods for the structural assessment of furnaces include visual inspections, analysis of thermal data, acousto ultrasonic-echo (AU-E) of the refractory lining and surveying of the key structural elements. Acoustic Emission (AE) non-destructive testing (NDT) technique has proven its capabilities for continuous monitoring of industrial installations and structures. Recently, Hatch Ltd. has been successful in applying acoustic emission for monitoring furnace tapblocks, and expanding the scope of the acoustic emission monitoring to the structural integrity of the entire furnace. The capability of detecting emissions related to the fracture development in the furnace shell, movement of the refractory, electrode arcing, combined with efficient source location algorithms makes an acoustic emission system a comprehensive tool for the real-time furnace integrity monitoring. In this paper the concept of such state of the art system for structural integrity assessment is presented. The initial results of the acoustic emission monitoring together with data analysis techniques are discussed.

Keywords: Acoustic emission, smelting furnace, structural integrity, continuous monitoring

1. Introduction

Various monitoring techniques such as Acousto Ultrasonic-Echo (AU-E), Taphole Acoustic Monitoring (TAM) and Infrared (IR) thermography have been evaluated as potential tools for structural integrity monitoring of industrial smelting furnaces [1-3]. They have proven their usefulness as being applicable for condition monitoring of metallurgical furnaces. Given the unique operating conditions of a smelting furnace, the most widely used monitoring techniques are based on the temperature measurements. They can be based on classic thermocouples or fiber-optic sensors.

Another common technique for furnace monitoring is based on direct measurements of furnace expansion in relation to the supporting structures or bindings (springs and stiffeners). These measurements, at times combined with the scanning of the topology of the entire vessel, provide valuable results and are quite commonly used. A good example of their application is the assessment of the growth of the furnace hearth. This phenomenon is expected to occur, for instance, during the furnace startup when a limited, controlled hearth growth is desired. All available measures must be applied to ensure the growth progresses both at the designed rate and within the expected time. Furnace startups, as well as shutdowns, are extremely complex operations technically and logistically [4]. Expert knowledge is required to design and execute them in a flawless manner. Yet problems tend to happen. The most common startup-related issue is the uncontrolled growth of the hearth (too small or too large, alternatively too slow or too rapid). During the startup, heat is applied to the furnace refractory, often by means of gas burners, prior to feeding ore to the vessel. The purpose of this initial heating is to seal the gaps between the adjacent bricks before smelting commences. Needless to say, the lack of proper sealing makes the furnace vulnerable to leaks. Analyzing the furnace topology, either by means of a full scan or by deformation measurements at critical locations, provides methods for evaluating the furnace conditions. It shows the effects of the furnace expansion, however, it does not provide sufficient details...
regarding the deformation process, partly due to the discrete nature of such measurements. This led to the conceptual development and implementation of a continuous, real-time furnace integrity monitoring system by means of acoustic emission. This paper discusses the concept of the method and illustrates the successful trial implementation of the technique in monitoring an electric furnace from startup to run-out. The results suggest that the technique can provide provisions for a timely response should any abnormal conditions be detected.

2. Furnace Shell Deformation

After the furnace is built and before the smelting can commence it is necessary to introduce heat to the hearth refractory in order to cause its thermal expansion. A certain portion of this growth contributes to filling of the gaps, intentionally left between the adjacent bricks at the construction stage to accommodate for the future expansion. As soon as the gaps are closed, further thermal expansion results in the growth of the hearth. This is manifested at the exterior of the vessel by deformation of the steel shell, mainly at the hearth level. Under normal circumstances the shell is designed to withstand such deformation. The forces and stresses caused by the expanding hearth refractory are balanced by hoop stress ($\sigma_\theta$) in the shell [5] (Figure 1).

![Figure 1. Forces and stresses in the furnace shell](image)

In certain cases the uncontrolled hearth growth and the related deformation of the steel shell can cause local separation of the shell from the refractory. This will significantly decrease the cooling efficiency, namely the heat exchange between the hot face and the cold face of the furnace. This becomes especially important if water spray cooling is the main or the only means for furnace cooling. As a result of insufficient cooling, the deterioration of furnace refractory and furnace structure as a whole would accelerate. Examples of extensive steel shell deformation are shown in Figure 2. These photos show cross-sectional view through a furnace wall. Clearly, the contact between the shell and the refractory was lost, and as a result, insufficient cooling to the bricks caused weakening of the structural integrity of the furnace.
Another case of significant expansion that was manifested by shell deformation and, eventually, fracture is illustrated in Figure 3. The dashed line indicates the original shape of the furnace shell (no expansion or contraction). Due to hydration, the volume of the furnace bricks grew locally beyond the acceptable limits. The extent of the radial expansion was measured as high as 40mm at location B11. This radial expansion is indicated in Figure 3 with the solid line.
Hydration of the refractory occurred when bricks were exposed to water while they were at high temperature. As a result the bricks deteriorated – they turned to powder and lost their load bearing capacity and, at the same time, their volume increased significantly. This was obviously manifested by extensive local radial deformation of a steel shell. As a result the steel plates, welds and stiffeners failed (Figure 4).

![Figure 4. Furnace shell failures: cracked steel plates and welds](image)

Similar modes of deterioration have been observed in many smelters, causing financial loss to the operations, and putting the operators in danger. In order to minimize these threats, a system for continuous monitoring of the furnace integrity has been proposed. This solution relies on applying a monitoring technique that would be capable of detecting the initial signs of deterioration and providing early warnings for the furnace operators. Hence, appropriate preventive means could be deployed before the damage becomes too severe and the furnace shutdown and rebuild are required. Analyzing various non-destructive techniques led to the selection of acoustic emission as an appropriate method for furnace structural integrity monitoring. The key purpose of the proposed technique is to locate and assess the type and the severity of the deterioration of furnace based on the continuous monitoring of the furnace shell deformation resulting from the internal deterioration processes.

### 3. Principles of Acoustic Emission

Acoustic emission is generated once a material sample subjected to forces or other stimuli reaches plastic deformation [6, 7]. This is schematically shown in Figure 5. The material yielding and cracking or, more precisely, the changes at the microstructure level release elastic energy detectable by an acoustic emission transducer.

![Figure 5. Acoustic emission detection](image)
There are many application of acoustic emission testing and monitoring of engineering structures. Recently, this non-destructive testing technique has been used to monitor smelting furnaces. In smelters, the thermal cycling is one of the key factors contributing to the structural deterioration of furnaces. The concept of acoustic emission activity during thermal cycling of a furnace is further discussed in this paper. It relates to the acoustic emission that is detected by the sensors installed at the level of the upper layer of the furnace hearth or in its vicinity (Figure 6).

![Sample AE sensor location](image1)

Figure 6. Sample location of the acoustic emission sensor on the furnace shell

During the initial heat-up of a furnace, acoustic emission is generated due to thermal expansion of the furnace. Once the designed and desired level of the furnace expansion has been reached, this portion of acoustic emission discontinues. During the steady state, no significant acoustic emissions are expected. During a cool down and a shutdown period, acoustic emissions are generated due to thermal contraction of the furnace.

4. Acoustic Emission Signal Source Location

The acoustic emission source location has a fundamental significance for the acoustic emission application in furnace condition monitoring. The source location ability gives the acoustic emission method the advantage over other monitoring techniques. It allows calculating the relative coordinates of the area of plastic deformation or micro-cracking across the entire furnace shell, based on the properties of the acoustic emission signals.

The source location problem originated in seismology, where the objective was to locate the focus of epicenter of an earthquake from seismograms obtained at points distributed over the Earth’s surface. Such source location was possible using an array of sensors and time of flight data, provided that the wave propagation characteristics between the source and the receivers were known. The source location problem is illustrated in Figure 7. For an array on \(i\) sensors their coordinates are: \((x_1, y_1, z_1), (x_2, y_2, z_2), \ldots, (x_i, y_i, z_i)\).

![Source location problem](image2)

Figure 7 – Source location problem
Only the first breaks of the P-wave arrival times are used for the location of acoustic emission events. From the Pythagorean theorem, the \( i \)-th sensor located at \( x_i, y_i, z_i \) will detect the signal when Equation 1 is satisfied (\( t_i \) is the time required to reach the \( i \)-th sensor, \( c \) is the wave velocity).

\[
(x' - x_i)^2 + (y' - y_i)^2 + (z' - z_i)^2 = (ct_i)^2
\]  

For an array of \( i \) sensors, \( i \) unique non-linear equations can be formed. If \( t_0 \) is the travel time required to reach the sensor closest to the source and \( \Delta t_i \) is the time difference between arriving the closest sensor and arriving the \( i \)-th sensor, such that: \( t_i = t_0 + \Delta t_i \). Then the source location can be determined by solving for the four unknowns \( x', y', z' \) and \( t_0 \) using four or more measured \( \Delta t_i \) values. In practical applications, large sensor arrays are often used to allow over-determination and enhance accuracy.

5. Trial Measurements – Case Study

The trial installation of the acoustic emission-based system for furnace integrity monitoring was conducted on a circular electric smelting furnace. Ten acoustic emission sensors were attached (using magnets) to the furnace shell at two levels around the skew bricks area, where the hearth expansion is expected to develop (Figure 8). The sensors formed triangular arrays, optimal for source location computations. The purpose of this trial installation was to validate the capabilities and limitations of the proposed technique, and not to carry out the actual monitoring.

![Figure 8. Acoustic emission sensors locations on the circular furnace shell](image)

Shortly after the installation the furnace experienced a localized metal leak, near one of the tapholes. The picture of the area of the leak is shown in Figure 9. Also in Figure 9 the locations of acoustic emission signals detected during the period of 24 hours prior to the metal leak are shown under taphole 3 (TH3). Clearly, the local degradation of the structural integrity that eventually resulted in a metal leak was detectable by the acoustic emission technique. The signal source location algorithms, as discussed earlier in the text, were accurate in calculating the location of the local damage.
6. Early warning prior to run-out

As shown in Figure 9, the acoustic emission can provide early warning prior to run-outs. In the case study discussed above the energy of the acoustic emission signals was used as the criterion to identify the impending leak. Other acoustic emission parameters are also being investigated in terms of their feasibility for this purpose. This includes the signal amplitude, duration and rise time. Also the acoustic emission activity is often a good enough indicator. It must be emphasized that the conventional means used for furnace monitoring often do not prove to be successful in detecting the events leading directly to run-outs. The deformation of the furnace monitored by the strain gauges (resistance or mechanical), or by topology surveys is helpful on indicating general problems related to the structural integrity of the vessels. However, typically the information provided is not sufficient to determine the scale or severity of the problem. Consequently, false alarms may lead to unnecessary shutdowns. Alternatively, the results may be misinterpreted, which leads to the underestimation of the actual risk. Based on the trial measurements it was established that significant acoustic emission events were generated at several cases: during the startup, shutdown, run-outs and possibly upset condition, such as hydration of bricks leading to local volumetric expansion. Other acoustic emissions due to background noises were filtered by careful selection of the amplitude thresholds, arrival time windows and signal frequency range. In the case of furnace monitoring all of these phenomena are related to extensive changes in stress distribution in the furnace. This feature of acoustic emission allows linking all the detectable acoustic emission sources to physical events occurring within the furnace, whether in the refractory or in the shell. Proper analysis of the acoustic emission signals can greatly increase the capacity of the furnace condition monitoring.

In order to improve the reliability of the acoustic emission monitoring system a complex algorithm for data analysis and interpretation is required. Given the huge amount of data collected during the continuous monitoring, pattern recognition software can be applied. The trial measurements results (as discussed in the case study) and the data from calibration on the given furnace will be used to train the algorithm to recognize impending hazards based on the particular sequence of acoustic emission events. The early warning base on acoustic emission source location as shown in Figure 9 in the preceding section is one example of such a chain of acoustic emission events. Should similar features be detected during the real-time continuous monitoring, an alarm or warning will be set off, depending on the intensity of the acoustic emission.
The greatest advantage of the acoustic emission method as compared to the other monitoring techniques is its capability of source location computations and pinpointing the positions of the significant events. A proper coverage of the furnace with sufficient number of acoustic emission sensors (depending mainly on the geometry of the vessel) provides the source location results within a few centimetres accuracy. This helps in identifying the weak spots of the furnace shell, the areas prone to metal penetration, the zones of progressing hydration and potentially other modes of deterioration. The intensity of acoustic emission signals in combination with the source location and other measurements such as strain changes and thermal changes, if available, can clearly indicate the area of furnace that is likely to cause failure.

7. Conclusions

The prototype system for continuous structural integrity monitoring of smelting furnaces (particularly circular electric furnaces) has been developed. The capabilities and limitations of acoustic emission technique for this application were established. This technique will complement other monitoring techniques, resulting in a comprehensive examination of the furnace’s operating conditions, and improving the safety, and the economic soundness of operations.

The information provided by the acoustic emission-based furnace integrity monitoring system, especially the locations and characteristics of the detected cracks in the shell, is readily applicable to the risk assessment evaluation of certain aspects of furnace operations. Furthermore, the development of an early warning system based on acoustic emission analysis is promising.

References