Refractory Lining Health Monitoring Based on Raman Optical Time Domain Reflectometry

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ABSTRACT

A fiber optic health-monitoring system for refractory lining in steel-making processes is presented. Its applicability as an early-warning system for lining damage is demonstrated by the results obtained in a field trial, in which 240 m of fiber was embedded in the lining of an electric arc furnace. The system is based on Raman distributed sensing and polyimide coated fibers in metal tube. The results presented from temperature cycling and calibration at temperatures up to 600 °C show that adequate accuracy and stability for the application can be attained.

Keywords: Raman distributed temperature sensing, fiber optics for harsh environments, refractory lining monitoring, high-temperature fiber-optic sensing

1. INTRODUCTION

This work aims towards a large-area health-monitoring system for refractory linings in steel making processes. The lining protects the steel shell of, e.g., ladles, furnaces, and converters from molten steel and slag, and it needs regular replacement to avoid break throughs. On average, 15 kg of refractories per ton of produced steel is expended globally.[1] The methods for monitoring lining wear vary from plant to plant and from process to process: visual inspection or laser scanning of empty vessels at regular intervals, online measurements using pyrometers, heat cameras, or point sensors in the metal shell are common examples.

Distributed fiber optic sensors offer unique benefits in these applications. Optical fibers can be integrated in the lining itself, and thereby provide a higher sensitivity than measurement done from the outside. They can cover a large area, and do not require a free line of sight. However, the temperature of the molten steel is greater than 1500 °C and the elevated temperature in this application, often 500-600 °C, is challenging. Polyimide coated fibers have sufficient protection up to approximately 300°C, which sets an upper temperature limit to most Raman-based distributed temperature sensor systems. For higher temperatures, metal coated fibers can, according to product specifications, be used up to 400 °C for Al, 600 °C for Cu in inert atmosphere and up to 700 °C for Au. Performing an accurate calibration for metal coated fiber in industrial applications have shown to be difficult due to unpredictable attenuation variations.[2,3] In the current application however, the main drawback with metal coated fibers is their price. There is always a risk that fibers in the refractory lining are damaged by molten steel, or during the relining process.

In this communication we present a system for refractory lining monitoring based on polyimide coated Fibers in Metal Tube (FIMT) and Raman Optical Time Domain Reflectometry (R-OTDR). Laboratory measurements show adequate tolerance to temperature cycling, and stability at 600 °C, which is a relevant temperature for the application. Results from a field experiment in an electric arc furnace (EAF) is also presented. The temperature in the refractory lining was monitored and the results demonstrate the applicability of the sensor as an early warning system for lining degradation. In the presented use case, the fiber is replaced at each relining of the furnace, which takes place a few times a year. This motivates the choice of the relatively inexpensive optical fiber over metal coated alternatives.

2. HIGH-TEMPERATURE CHARACTERISATION OF THE R-OTDR BASED DISTRIBUTED TEMPERATURE SENSING SYSTEM

Preparatory measurements were made in a laboratory setting for calibration and stability verification. The optical fiber used, was a FIMT, with inner/outer tube diameters of 1.4 mm/1.8 mm. The selected optical fiber was a standard graded index multimode fiber (MMF) with polyimide coating, fabricated at the RISE fiber drawing facilities.

The FIMT was coiled with a diameter of 40 cm and placed in a furnace. Four reference thermocouples were placed on the circumference of the coil to cater for any spatial variations in temperature. The fiber length in the furnace was 40m, long enough to ensure that edge effects at the oven entry could be avoided. The temperature was increased from room temperature to around 600 °C in several steps and a commercial R-OTDR (AP Sensing, N4586A) was used to perform the distributed temperature measurements. All measurements were made dual ended, with an acquisition time of 3 minutes and a sampling interval of 25 cm, which gave a sufficient accuracy within of a few degrees Celsius. For each temperature setting, the oven was given enough time to stabilize properly.

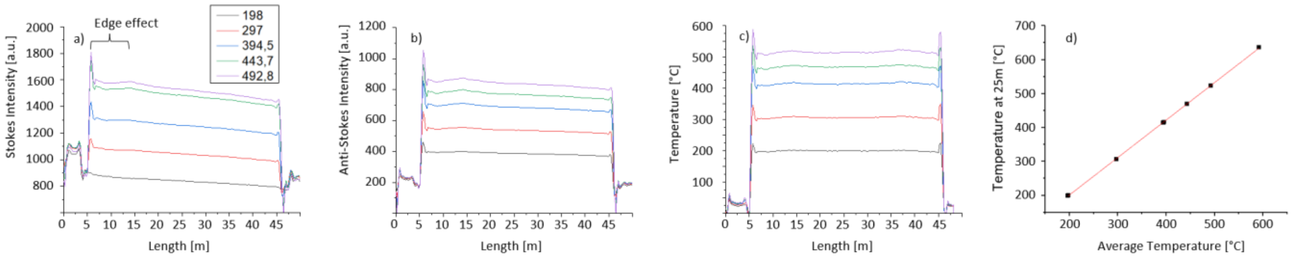

Figure 1. Evolution of the (a) Stokes and (b) anti-Stokes signals and (c) measured temperature of a Ge-doped MMF in a metal tube at different temperature settings. (d) A plot showing the linear relation between the average of the four reference temperature probes (horizontal axis), and the R-OTDR temperature at 25 m (vertical axis).

The intensity evolution of the backscattered Stokes, and anti-Stokes signals, and the measured temperature is displayed in Fig. 1 (a-c). At the oven feedthrough, at 5 m, there is an overshoot that might be explained by chromatic dispersion.[4] After the entry point, in the range 5 to 13 m, the signals feature an irregularity, which is also reflected in the dual-ended temperature trace. To our experience, this is typical for large steps in temperature and reduces the useful fiber length since the first few meters are unreliable. For the middle part of the heated fiber, the factory calibration of the R-OTDR produced a linear reading relative to the reference sensors from room temperature to 600 °C. A multiplicative factor of 0.92 was applied to the R-OTDR reading to adjust the slope in Fig. 1 (d).

To assess the stability and the influence of temperature cycling, a 25-day thermal cycling test was performed. In this experiment a different R-OTDR instrument was used (N4386B Linear Pro, AP sensing). The cycles varied between room temperature and 500 °C and a with a two-day excursion to 600 °C. The temperature and the optical losses were monitored, and the results are shown in Fig. 2. For temperatures up to 300 °C, the losses were low, indicating that the fiber was in good condition. A rapid loss increase was observed as the temperature rose from 300 °C to 500 °C and the loss varied unpredictably after that. Despite the varying loss, the temperate reading was stable within ± 5 °C relative to the thermocouples, with exception for a one-day settling time, see Fig. 2(b). This initial misreading coincides with the polyimide being burnt off when the temperature was raised to 500 °C for the first time.

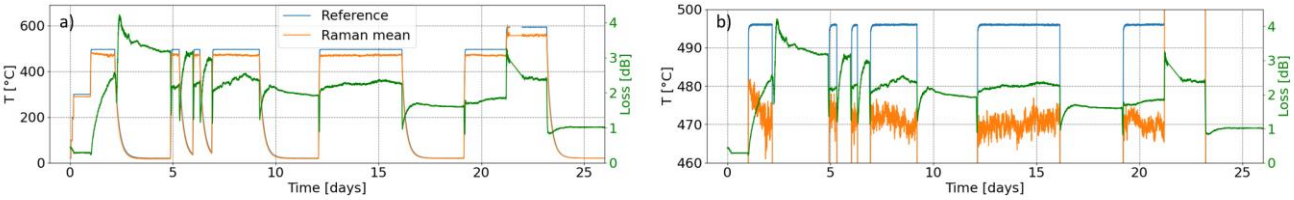

Figure 2. Temperature cycling showing repeatable temperature reading despite varying optical losses. The gap in the data after approximately 22 days was due to a temporary disconnection.

3. REFRACTORY LINING MONITORING IN AN ELECTRIC ARC FURNACE

A field trial was carried out in the electric arc furnace (EAF) at Höganäs’s steel mill in Halmstad, Sweden. In an EAF, illustrated in Fig. 3(b), scrap steel is molten using a continuous electric discharge. The furnace in this study was equipped with a monitoring system in the form of 12 Pt100 temperature sensors mounted in the steel shell of the furnace bottom. The lining is also inspected at regular maintenance breaks when the furnace is completely emptied of molten steel. The cooling and reheating of the lining reduces its lifetime and therefore the inspections are limited to these scheduled events.

3.1 Installation

The fiber optical sensor cables were installed during a partial relining and covered approximately 3x5 m^2 of the furnace floor. The cables consisted of FIMT, as described above, inserted into a 5-mm steel conduit, which served as an additional mechanical protection, see Fig. 3(a). The lining was composed of a layer of refractory bricks closest to the steel shell and a 0.5-1 m thick layer of refractory powder on top of the bricks. The fiber cables were installed on top of the brick layer, and were then covered by the insulating powder, see Fig. 3(b). A total of four cables, each 60 m long, were installed, and both ends of the cables were routed out through a feed through to enable dual-ended measurement of the four fiber loops.

To localize the temperature readings from the R-OTDR and enable 2D-monitoring, the fiber layout was recoded with a series of photos taken during the installation. The photos were processed using a custom software to map the fiber distances to positions on the furnace floor. The heatmaps in Fig. 4 were generated from the mapped temperature data by linear interpolation.

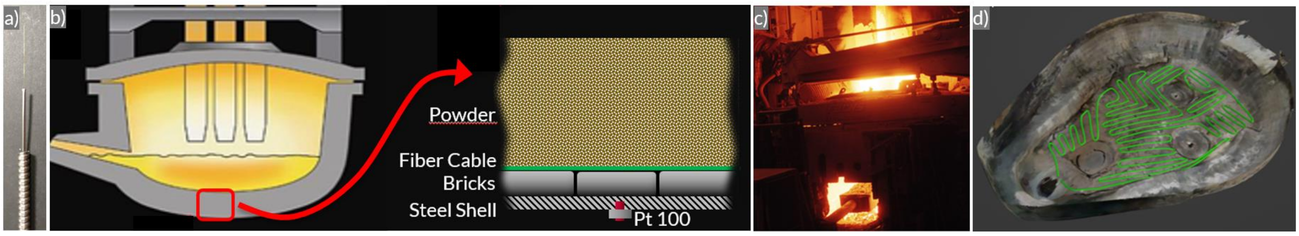

Figure 3. (a) The fiber optic sensor cable consisting of a FIMT in a protective conduit. (b) A schematic picture of a generic EAF and a detail showing the placement of the fiber sensor, the location of the Pt100 elements and the lining structure. (c) The EAF in the Halmstad steel mill during operation. (d) A 3D scanned image of the inside of the same EAF showing a schematic layout of the optical fiber cable.

3.2 Results of the lining monitoring

Initially, a slow and steady increase in temperature and an expected temperature distribution was observed, see Fig. 4(a). Later, a hotspot developed, and the temperature increased locally from 550 °C to above 1000 °C in less than 12 hours, an indication of lining damage. Fig. 4(a,b) illustrates this evolution. During the following five days several similar hotspots developed, and the hot area grew, as seen in Fig. 4(c). It was later confirmed that these events coincided with a period of damage in the lining.

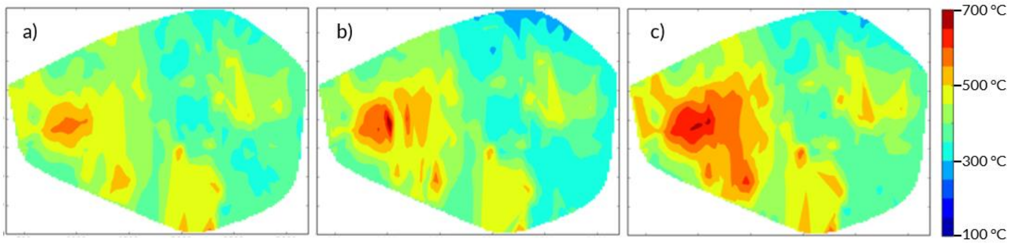

Figure 4. Heatmaps showing the evolution of the temperature in the EAF lining. (a) An expected temperature distribution a couple of weeks into the experiment. (b) Development of a hotspot 1 day after a). (c) Five days after (b).

The detected hotspots reached temperatures >1000 °C, which caused local fiber damage and about 1 m of the fiber around each hotspot was therefore excluded from the data. This can be seen in Fig. 5(a) where the temperature increases rapidly and then quickly drops. The sudden drop means that the damaged point was excluded from the analysis at that point in time. As new hotspots occurred, more sections of the fibers were excluded, and eventually, the fibers broke at the hotspot positions. After the fiber breaks, the measurements were switched from dual-ended to single ended measurements from both ends, while excluding the damaged ends from the acquired data. Eventually, since the input and output of the cables were exposed to the same hot area, fiber breaks occurred near the start and the end of 3 out of 4 fiber cables.

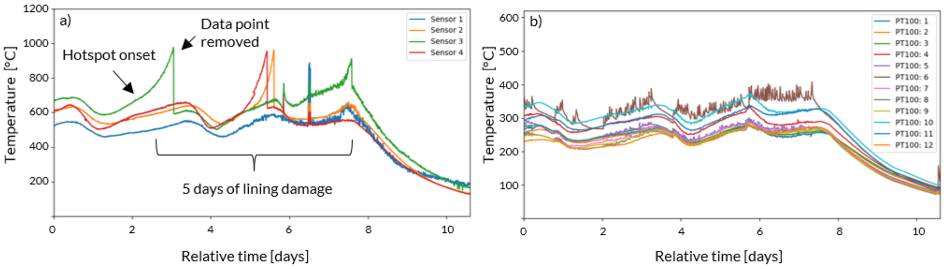

Figure 5. (a) The highest temperature reading for each of the four fiber optic cables deployed in the lining. (b) data for the same time period from the Pt100 elements placed in the bottom shell for lining health monitoring. The fiber clearly signalled hotspots that were not detected by the Pt100 sensors. The sharp temperature rises detected by the fibers coincided with problems with lining damage in the hot area visible in the heatmaps in Fig. 4.

4. CONCLUSION AND FUTURE WORK

We conclude that an adequate measurement repeatability can be achieved with polyimide coated fibers over weeks of temperature cycling between room temperature and 500 °C, despite variations in optical losses. It is also concluded that the fiber optic monitoring shows potential to be used as an early warning system for lining damage. The temperature rise was obvious in the fiber optic data, but the lining damage was only detected later when parts of the lining was found floating in the molten steel. It can also be noted that the damage was not visible in the temperature data acquired by the Pt100 elements in the shell.

The fragility of the optical fibers remains a challenge and exposure to molten metal is a risk. We have previously measured during 3 months at temperatures between 500 and 650 °C, in the same application without any fiber breaks, so the fibers can survive if they are not affected by local hotspots. An obvious improvement would be to route the fiber cables differently to minimize the effects of local damage. Input and output of the fiber should be separated so that measurements can be done from both ends independently in case of a fiber break.

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