Optical fiber acoustic emission system for monitoring molten salt attack

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Abstract

We developed an advanced optical-fiber acoustic-emission (AE) monitoring system with a phase-compensation feedback circuit, and detected AE signals from molten-salt attack of Type 304 stainless steel pipe. The system is a Mach–Zender type laser interferometer, consisting of a diode laser, two single-mode fibers of sensing and reference arms and two photodiodes as detectors of interfered laser beams. Outputs of the photodiodes are combined in a differential amplifier, which can extract error signal (noise) and significantly improve the S/N ratio by utilizing a specially designed feedback circuit. An optical fiber coated by UV-cured polymer can detect AE signals at 673 K and be utilized to monitor the cylinder wave from oxidation at elevated temperatures. The sensor monitored the weak longitudinal (L-) mode as well as the flexural (F-) mode of the cylinder wave AE signals when it was wound on the pipe surface by several turns. Source locations of AE signals in the axial direction were determined from the arrival time differences of the L- and F-mode at a selected frequency. The system measured AE signals from frequent fractures of the oxide film produced by molten salt attack (85 mol% V$_2$O$_5$ + Na$_2$SO$_4$) at 1073 K. AE sources, detected during cooling of the pipe, were located in the zone severely attacked by the molten salt.

Keywords: Optical fiber sensor; Acoustic emission; Heat-resistant sensor; Oxidation; Molten salt attack

1. Introduction

Acoustic emission (AE) system utilizing PZT type transducers has difficulties in monitoring AE signals of high temperature equipments. Difficulty arises from the low Curie temperature (573 K) of the PZT element. Thus the AE signals have been monitored via rod-type wave guide with sufficient length. The AE signals detected via the wave guides, however, contain multi-reflected waves. This makes detailed analysis of AE signal difficult [1]. It is generally difficult to monitor the weak longitudinal (L-) mode of cylinder wave AE by the PZT sensor, while the L-mode is a useful mode wave for the source location and source wave analysis of AE [2].

There are some heat resistant AE sensors on the market. A sensor using LiNbO$_3$ element is reported to be heat resistant up to 833 K [3], but is massive and expensive. Handling of massive sensors is generally difficult, especially in mounting them on small size hot pieces. Development of small, broadband and heat-resistant AE sensors has been desired for long time, but not on the market at present.

We developed an optical fiber AE monitoring system [4]. The sensor of this system is a telecommunication optical fiber coated by UV-polymer, and is light-weight, flexible and heat resistant to the temperatures higher than the Curie temperature (573 K) of the PZT element [5]. We first measured the heat resistance of the coated optical fiber sensor and then monitored AE signals from molten salt attack of Type 304 stainless steel pipe. Source locations of AE signals were estimated from the arrival time difference of L- and F-modes of cylinder wave. A number of cylinder wave AE were detected by the optical fiber during cooling of the pipe from 1073 K. Source of detected AE signals were located in the zone with thick non-protective oxide film produced by catastrophic oxidation from the molten salt. The system was demonstrated to be a heat resistant sensor and can measure the weak cylinder wave AE signals at around 600 K. The system is particularly excellent in monitoring the frequent cylinder wave AE signals since the sensitivity of the system is significantly improved by multiple winding of the sensor fiber.

2. Optical fiber acoustic emission monitoring system

Fig. 1 shows schematic diagram of the developed system. The system is a homodyne Mach–Zender type laser interferometer with a phase-compensation feedback circuit.
The system is composed of the sensing and feedback control section. Laser beam emitted from a laser diode is split into sensing and reference arms through a $1 \times 2$ optical fiber splitter. Two laser beams transmitted through the two arms are combined by a $2 \times 2$ coupler and then detected by two photodiodes. Two signals detected by the photo diodes were then fed to a difference amplifier to improve the S/N ratio by the feedback section. The feedback section is required to minimize the low frequency drift or noise due to vibration of fiber and temperature change.

Here, intensity of output signal from interferometer is given by Eq. (1).

$$I = 2(1 + \cos(\phi(t)))$$ (1)

where $\phi(t)$ is the phase modulated by AE signal. When the $\phi(t)$ is small, the output intensity is almost constant and sensitivity is quite low since the slope of cosine function is almost same for small $\phi(t)$. To make the system sensitive, the phase difference between signal and reference beam should be maintain at the $\pi/2$ or quadrature condition. Quadrature condition is expressed by Eq. (2).

$$I = 2(1 + \cos(\phi(t) + \pi/2)) = 2(1 + \sin(\phi(t)))$$ (2)

Intensity is proportional to the sine of the phase $\phi(t)$. Then we realized a feedback control using a rectangular PZT actuator as a phase shifter. The reference fiber was glued rigidly on a PZT actuator of 20 mm length $\times$ 3 mm width $\times$ 2 mm thickness so as the fiber be in the vibration direction of the actuator. Feedback control was achieved utilizing small changes of the reference fiber length by the PZT actuator driven by an error signal. Error signals must correspond to the low frequency drifting. Thus this signal was produced by integrating the output with an operational amplifier to which was fed the low frequency component, extracted by a low-pass filter with cut-off frequency of 400 Hz. Fig. 2 compares outputs.
of the system with and without the feedback circuit. Large oscillation of the system without the feedback control was eliminated by the feedback circuit.

3. Heat resistance of coated sensor fiber

We first studied heat resistance of the coated fiber sensor by using the method of Fig. 3. The sensor fiber was wound 10 turns over the outer surface of a steel rod of 35 mm diameter and 1000 mm length at the exit of tubular furnace. Cylindrical waves were excited by a PZT transmitter (PAC PICO, center frequency 450 kHz) mounted at the left edge of the rod. Center portion of the rod was heated by the tube furnace. Temperature at the fiber sensor was measured by a thermocouple. Fig. 4 shows the detected waves at 300, 473 and 673 K. Output of the wave at 673 K is smaller than that

![Fig. 3. Experimental setup for studying heat resistance of the optical fiber sensor.](image1)

![Fig. 4. Cylinder wave AE signals detected at 300, 473 and 673 K by using coated optical fiber sensor.](image2)

![Fig. 5. Effect of fiber winding on the AE waveform.](image3)

![Fig. 6. Change of the maximum output of L(0,1) mode wave with turn number of wound sensor fiber.](image4)
at 473 K. The fiber failed at around 780 K. Adoption of bare fiber or the fiber coated by heat-resistant polymer such as Kevlar can improve the heat resistance of the sensor. We utilized, however, the commercial UV-coated optical fiber on the market this time.

4. Sensitivity of sensor fiber to cylinder wave AE signals

Developed system is sensitive to the in-plane motion of elastic wave or the change of glued fiber length. Thus the sensor can monitor the weak L-mode cylinder wave when it was wound on the pipe surface by several turns. Fig. 5 shows the output of the system as a function of turn number. Here the optical fiber was wound on the 30 mm diameter aluminum pipe of 1 mm thickness at 100 mm from the transmitter (PICO). Output increases with increasing the turn number and can detect the initial weak L-mode. As shown in Fig. 6, the maximum amplitude of the L-mode increased with turn number with a slope of 9.94. We used 20 turn fiber as the sensor in the following test. As the width of the 20 turn wound fiber becomes approximately 6 mm, too much winding of the fiber makes the source location accuracy poor.
5. Source location of cylinder wave AE by single fiber sensor

As the whole length of the optical fiber acts as one AE sensor, we need multi-channel system for the source location of AE signals. This situation is the same for the system using the PZT sensor. For the cylinder wave AE signals, we can, however, estimate the location of AE source in the axial direction from only single AE wave if they contain both the L- and F-mode components. Source location of cylinder wave AE can be estimated from the arrival time difference of L- and F-modes at selected frequency. This method was previously used for the PZT AE system [6]. Location accuracy was, however, poor since the PZT sensor could not monitor the weak L-mode arrival correctly. Contrary to the PZT sensor, the fiber sensor can monitor the weak L-mode. Location scheme and accuracy by this method were studied using the experimental setup of Fig. 7. We monitored the cylinder wave by the sensor fiber wound by 10 turns over the steel tube of 30 mm diameter, 4 mm thickness and 1000 mm length. Distance: Z of the sensor to the source (PZT transmitter) was changed from 100 to 400 mm. The sensor detected the first arriving L-mode and following F-mode as shown in Fig. 8. Contour map of wavelet coefficients represents the dispersion curves of various modes of the cylinder wave. Here the solid lines are theoretical velocity dispersions of L(0,1), L(0,2), F(1,1) and F(1,2) modes. Strong component (dark part) at 85 kHz coincides the F(1,1) mode at 2060 m/s. First and weak coefficient at 85 kHz corresponds to the L(0,2) mode at 4480 m/s. At 85 kHz, the peaks of two modes, L(0,2) and F(1,1) can be detected clearly.

Source location in the axial direction is then estimated by using the arrival time difference $\Delta t$ of these two modes by Eq. (3). Average distance errors for the sources in the range from 100 to 400 mm are 21.2 mm and 9.1%.

$$Z = \left( \frac{V_{L(0,2)} V_{F(1,1)}}{V_{L(0,2)} - V_{F(1,1)}} \right) \Delta t$$  \hspace{1cm} (3)

6. Monitoring of AE signals from molten salt attack of type 304 stainless steel Pipe

Accelerated oxidation of heat resistant austenitic alloys by molten salt is well known to cause the most dangerous damages in boiler tube and gas turbines [7]. We monitored AE signals from the oxidation in air and by the molten salt for Type 304 stainless steel pipe of 30 mm diameter. Shown in Fig. 9 is an experimental setup for the oxidation test and AE monitoring. Type 304 pipe of 1000 mm length was heated up to 1073 K at its middle portion by a tubular furnace of 280 mm length. The sensor fiber was wound over the tube by 20 turns at the position from 80 mm from the left end of the furnace. Here the origin of the axial direction $z$ is set at the location of the fiber sensor. Temperature at the sensor fiber is measured as 573 K. We also used two small AE sensors (PAC Type PICO) at both ends of the pipe with sufficiently low temperature. Signals from two PZT sensors and optical fiber system were digitized at 200 ns interval with 8192 points. Sampling rate is 30 events/s. This rate is limited by the digitizer used but much faster than that of the system using the Bragg grating fiber sensor [8].

We monitored no AE during the atmospheric oxidation test at 1073 K for 10.8 ks and also during the cooling of the pipe. The surface of the pipe suffered slight oxidation and produced blue inference oxide film. Next we painted 1.3 g of mixed salt (85 mol% V$_2$O$_5$ and Na$_2$SO$_4$, melting temperature of 873 K) over the upper portion of the pipe at $z=250$ mm and heated the
pipe for 10.8 ks at 1073 K. We detected no AE signals during the heating, but monitored a number of AE signals during cooling of the pipe. Fig. 10 shows cumulative AE change with temperature history of the pipe in the furnace. We observed a rapid increase of AE signals from 873 to 615 K and slow increase below 615 K. Generation rate of AE above 615 K is seven times larger than that below 615 K. Owing to the fast sampling rate and high sensitivity of the system, we first revealed the change of AE generation rate or fracture frequency of non-protective thick oxide scale (magnetite).

Fig. 11 shows an example of AE waveform (E.C. 290) and time transient of wavelet coefficient at 85 kHz. We detected both the weak L-mode and strong F-mode packets. Location of this wave was estimated at $z = 244$ mm at which the salt was painted. Fig. 12 compares the change of the first L(0,1) mode amplitude with time. The upper Fig. 12 represents the AE signals above 615 K. There observed large variation of the amplitude, but stronger AE signals at temperatures below 615 K. The data at 100 mV designate the overshooting the vertical scale. We heard large sound after 11.3 ks. We analyzed size distribution of dropped oxide scale as a function of pipe temperature. The scales dropped above 615 ks is splat-shaped in the range of 0.04–0.15 mm, while that above 615 K is sharp edge triangle or rectangular of 0.05 to 0.4 mm. This implies that rapid temperature drop above 615 K causes spallation of small scales. Large sound and strong AEs below 615 K are due to fracture or spallation of large size scales. Change of source location was overlaid on the surface photograph in Fig. 13. AE sources were located in wide range from $z = 150$ to 350 mm over which thick black magnetite film was observed. This is because the molten salt spread over the pipe surface and produced catastrophic oxidation. There observed no AE

![Figure 12](image1.png)

Fig. 12. Change of L(0,1) mode amplitude of AE signals detected above (upper) and below 615 K (lower).

![Figure 13](image2.png)

Fig. 13. Change of source location of AE signals with time and photographs of upper surface of Type 304 stainless steel pipe.
sources in $z<150$ mm without thick oxide film. Some AE events and black oxide film at around $z=350$ mm are due to the spilt salt during painting.

7. Conclusion

We developed an optical fiber AE monitoring system and monitored AE signals from fractures of non-protective oxide films produced by molten salt attack of Type 304 stainless steel pipe at elevated temperatures. Results are summarized below:

1. Optical fiber sensor can detect cylinder wave AE signals at 673 K. Sensitivity of the sensor can be significantly improved by multiple winding on the pipe surface. It can detect weak Lo-mode of the cylinder wave.

2. Location of cylinder wave AE signals was estimated from single AE wave with both components of longitudinal and flexural modes. Accurate source location was possible for the cylinder wave AE signals detected by the optical fiber sensor.

3. The system monitored cylinder wave AE signals from fractures and/or exfoliation of non-protective oxide films of Type 304 pipe by molten salt attack at 1073 K. The system detected 780 events of cylinder wave AE signals during cooling of the pipe and first revealed the fracture frequency of non-protective oxide film. Source of AE events were located over the pipe surface attacked by spread molten salt.

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