Laser-induced surface acoustic wave technique for precise depth measurement of stress corrosion cracking

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Abstract. A new method to evaluate a crack depth is introduced. Surface acoustic wave generated by Q-switched Nd:YAG laser (wavelength: 532 nm) and detected by frequency-stabilized long pulse laser (wavelength: 1,064 nm) coupled with confocal Fabry-Perot interferometer is used to evaluate a depth of surface-breaking tight crack. When the generated surface acoustic wave propagates through a crack before it is detected, only the lower frequency component is observed at the detection point due to interaction between the broadband surface acoustic wave and shallow crack. Energy of surface acoustic wave penetrates about its one wavelength into the propagation medium; it means that surface acoustic wave with higher frequency component localizes only thin layer from the surface and one with lower frequency component easily travel through cracks if it is shallow. A frequency response analysis technique, as well as an amplitude response analysis, of the surface acoustic wave is developed to quantitatively evaluate the depth of cracks. Several stress corrosion cracks introduced on type 304 stainless steel plates by immersing corrosive solution with tensile stress are prepared to verify the performance of this method. The results demonstrate the error of this depth measurement method is estimated at less than 0.3 mm.

1. Introduction
Initiation and growth monitoring of surface crack, such as stress corrosion cracking (SCC) and fatigue cracking is important issue for many industrial non-destructive testing (NDT) applications. In particular, due to the recent remarkable innovation on maintenance technologies [1], detection and accurate depth measurement of shallower, typically sub-mm to a few mm deep, surface cracks is important to determine efficient maintenance strategy.

Our final goal is to establish a method for sizing surface crack having a depth of about 0-3 mm. Laser-ultrasonics can offer higher spatial and temporal resolution than conventional contact type transducer since it features a very small generation and detection spot size, say less than 1mm, and very broad generation and detection response. Using the laser-generated and -detected surface acoustic wave (SAW), some pioneer studies to detect and size surface cracks in metal have been performed since 1980’s [2]. In particular, feasible concepts based on the use of frequency response of transmitted SAW have been already introduced [3][4] and they demonstrated good results through some experiments with artificial slots. In this paper, we firstly carefully observe behaviours of laser-induced SAW transmitted through a surface crack, not only artificial slots but also SCCs, to obtain deeper understandings of the phenomena. Then we discuss a method to obtain accurate crack depth based on the understandings.
2. Experimental Setup

An experimental setup for laser-ultrasonic testing is schematically shown in figure 1. A Q-switched Nd:YAG laser having a wavelength of 532 nm, a pulse duration of 5-10 ns and a pulse energy of typically 30 mJ is used as the generation source of ultrasound. When a laser pulse from the generation laser is launched onto the surface of the test piece, longitudinal wave, shear wave and SAW are excited at the same moment through the ablative interaction process between the laser pulse and the materials.

Another Nd:YAG laser having a wavelength of 1,064 nm, a pulse duration of 90 μs and a pulse energy of 2.5 mJ is used for the detection of ultrasound. The detection laser is irradiated at the point 15 mm away from the generation laser spot.

A slot or a crack formed on the test piece (details are described later) is arranged between the generation and detection spots. The generated SAW transmits through the crack and is detected as micro surface displacements by the detection laser coupled with a confocal Fabry-Perot interferometer (CFPI). The CFPI has a cavity length of 0.35 m and finess of about 22.

The ultrasonic signal from the photodetector in the interferometer is converted, processed and stored in the signal processor.

Regarding test pieces (TPs), 12 slots, each of which has a dimension of 30 mm long, 0.2 mm wide and from 0.2 to 2.4 mm deep, are machined on type 304 stainless steel plates. Also, 2 long SCCs (TP#SCC03 and TP#SCC06) are introduced on the other type 304 stainless steel plates. The cross section is observed as figure 2 after a series of laser-ultrasonic experiments and the actual average depth of SCCs are measured as 0.5 mm and 1.8 mm. For each SCC, 10 measurement points are defined with an interval of 5 mm along the SCC.

![Figure 1. Experimental setup for laser-ultrasonic testing](image)

![Figure 2. Typical cross-section observation result (TP#SCC03)](image)
3. Results and Discussions

3.1 Amplitude change of transmitted SAW

Acquired raw waveforms with the slots are shown in figure 3. They obviously indicate that the amplitude of transmitted SAW drastically decreases with the increase of slot depth. Signal amplitudes against the slot depth are plotted in figure 4(a). Based on the plots in figure 4(a), we obtain a fitting equation:

\[ y = \exp(-1.6x) \]  

(1).

By using equation (1), we calculate slot depths from the observed signal amplitudes. Also, 20 data from the SCC TPs (10 data from 2 SCC TP) are calculated by the same manner. The result is shown in figure 4(b). Important note that the behaviours observed on the slot TPs and SCC TPs are mostly the same. One more important point is obvious trend that measured depths increase with the increase of the actual depths is observed but lack of linearity is also observed. Underestimation in the deeper crack depth region can be explained as “saturation”, which means that the energy of SAW cannot reach to the region any more. Instead, data show rather a logarithmic behaviour drawn by the dotted line in figure 4(b). Therefore the difference should be systematic and we should establish a model to explain this phenomenon.

Figure 3. Acquired raw waveforms with the slots

Figure 4. (a) Amplitude change of SAW against crack depth and (b) Relation between actual and measured crack depth
3.2 Frequency response of transmitted SAW
Frequency responses of the transmitted SAW through the slots are shown in figure 5. As shown in the figure 5, the peak frequency shifts toward the lower frequency region and the peak amplitude decreases with the increase of slot depth. The cut-off (first node) frequencies against the slot depth as well as the SCC depth are plotted in figure 6. Important note that the behaviours observed in the frequency domain on the slot TPs and SCC TPs are mostly the same again. One more note that the plot with slot is divide into 2 branches denoted with the white and black diamonds in the figure 6. This caused by the "dent" around the peak frequency given by 0.4-1.2 mm depth slots in the frequency response curve, figure 5.

3.3 Combination use of amplitude change and frequency response
Through the discussion in the section 3.1 and 3.2, we found that both amplitude and frequency response of the transmitted SAW gives value information of crack depth. The amplitude of SAW is

![Figure 5. Frequency response of transmitted SAW with slots](image1)

![Figure 6. Cut-off frequency of transmitted SAW against slot/SCC depth](image2)

![Figure 7. (a) Integration value of SAW against slot/crack depth and (b) Relation between actual and measured crack depth evaluated by ](image3)
exponentially decreasing with the increase of slot/crack depth; however the linearity is slightly lost in particular in SCC data. Also, the cut-off frequency decreases with the increase of slot/crack depth but some discrepancy observed around the crack depth of 0.4-1.2 mm maybe due to the small dent around the peak in the frequency profile. Therefore, we propose that the combination use of amplitude and frequency information. This idea is realized by introducing an integration value, \( I(d) \);

\[
I(d) = \int_{f_m}^{f_M} f \cdot P_{SAW}^d(f) df
\]

(2).

Here, \( f \) is frequency, \( P_{SAW}^d(f) \) is a frequency profile of transmitted SAW at the slot/crack depth of \( d \), \( f_m \) and \( f_M \) are minimum and maximum frequency of region of interest, respectively. In this study, \( f_m \) and \( f_M \) are chosen as 1 MHz and 8 MHz.

Figure 7(a) shows the calculation results of \( I(d) \) for all slot/crack data against actual depth. The fitting equation obtained from figure 7(a) gives the final relation between the measured and actual depth of slot/crack as shown in figure 7(b). The statistical analysis on the error between the measured depth (plots in figure 7(b)) and actual depth (plain line in figure 7(b)) is also shown in table 1.

| Table 1 Statistical analysis result of slot/crack depth measurement |
|-------------------------|-------------------------|
|                         | Slot (mm) | SCC (mm) |
| Error average           | -0.00      | -0.02    |
| Maximum error           | 0.39       | 0.49     |
| RMS error               | 0.27       | 0.32     |

4. Conclusion
Based on the experimental data including SCC and their analysis results, we confirm that the amplitude of SAW is exponentially decreasing with the increase of slot/crack depth; however the linearity is slightly lost in particular in SCC data. Also, the cut-off frequency decreases with the increase of slot/crack depth but some discrepancy observed around the crack depth of 0.4-1.2 mm maybe due to the small dent around the peak in the frequency profile. Based on these careful observation, we suggested a new method for evaluating a depth of surface crack using both frequency response and amplitude change. The results obtained in slot samples and SCC samples show that the error average of this depth measurement method is 0.0 mm and its RMS error is 0.3 mm in the range between 0.0-3.0 mm.

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