High-Selectivity Ultrasonic Imaging of Closed Cracks Using Global Preheating and Local Cooling

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High-selectivity ultrasonic imaging of closed crack is an important subject for avoiding not only underestimation but also misidentification of closed cracks. Thus far, the combination of load difference phased array (LDPA) and the crack opening method (GPLC) that combines global preheating (GP) and local cooling (LC) has been verified. Here the LDPA utilized the subtraction of the phased array (PA) images before and after the application of thermal stress induced by GPLC. However, as the cooling time increased, the change in wave velocity depending on the temperature within specimen is not negligible. This results in ghosts that degrade the selectivity of closed crack in subtracted images. In this study, on the basis of the finding that the change in crack response is faster than that in the wave velocity during GPLC, we propose a short time interval subtraction (STIS) method as an option in LDPA. This is based on the subtraction of a PA image from that obtained before a short time interval. It was experimentally verified in a closed fatigue crack specimen made of aluminum alloy. [doi:10.2320/matertrans.I-M2014810]

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1. Introduction

Measurement of crack depth is important for the safety and reliability of aged structures and materials. Crack depth can be measured by ultrasound if cracks are open, since ultrasound is scattered at the crack tip. However, if cracks are closed because of compressive residual stress and/or the oxide film generated between the crack faces, ultrasound is transmitted through the closed crack. This leads to underestimation or nondetection of cracks, resulting in catastrophic accidents.

To measure closed-crack depths, we have developed a closed-crack imaging method, the subharmonic phased array for crack evaluation (SPACE), on the basis of the subharmonic generation by short-burst waves and the phased array algorithm with frequency filtering. SPACE provides fundamental array (FA) images at the frequency f and subharmonic array (SA) images at the frequency f/2, visualizing the open and closed cracks, respectively. We have verified it in closed fatigue cracks and stress corrosion cracks (SCCs).

However, when short-burst input waves are used to obtain a high temporal resolution, not only closed cracks but also linear scatterers appear in SA images, since the spectra of the waves scattered at linear scatterers leak in the band-width of superharmonic and subharmonic waves. This results in ghosts that degrade the selectivity of closed cracks in SA images. However, if a deep crack is extended from a back surface with a known simple geometry, the crack depth can be accurately measured by SPACE, since the response of crack tip can be readily identified, as shown in Fig. 1(a).

However, if a short crack exists in the vicinity of a back surface with unknown complicated geometries, e.g., due to corrosion, or near weld defects such as blow holes, the identification of closed crack is difficult, as shown in Figs. 1(b) and 1(c).

To solve this problem, we have proposed a load difference phased array (LDPA), which is based on the subtraction between phased array images at different loads. The principle of LDPA was verified in a fundamental experiment using a servohydraulic testing machine for applying external tensile loads to cracks. However, the servohydraulic testing machine is not practical because it is large and heavy.

As another approach for applying a tensile stress to cracks, we have developed a practical crack opening method (GPLC), that combines global preheating (GP) and local cooling (LC), of applying tensile thermal stress to cracks. GPLC can readily increase the tensile stress by varying GP temperature so that it enables us to open tightly closed cracks which cannot be opened only by LC. It was demonstrated that the combination of GPLC and LDPA is useful in enhancing the selectivity of closed cracks, where a linear phased array (PA) image before LC was subtracted from that after the onset of LC for LDPA.
However, GPLC involves in changing the wave velocity of specimens because thermal stress is generated by the temperature change within the specimen. This result in ghosts that degrade the selectivity of closed crack in the subtracted image created by LDPA.

In this study, we propose a short time interval subtraction (STIS) method, as an option of LDPA, to subtract a PA image from that obtained before a short time interval. Then, we show that the combination of GPLC and the STIS method in LDPA is useful in achieving high-selectivity imaging of cracks.

2. Principle

Figure 2 shows the combination of GPLC and LDPA for enhancing the selectivity of closed cracks. The basic concept is that a closed crack is opened by GPLC, and thereafter, only the crack response is extracted by subtracting the PA images at a different thermal stress by LDPA. The imaging of welded parts is considered, and weld defects, the back surface, and cracks are visualized by PA.

After the GP of the specimen, the back surface and a weld defect are imaged by PA (Fig. 2(a)), whereas a closed crack is not imaged because ultrasound is transmitted through the closed crack. The image intensity at position $r$ at time $t_B$ before LC is given by

$$I(r, t_B) = b_1 u(r_W(t_B)) \delta_A(r - r_W(t_B)) + b_2 u(r_G(t_B)) \delta_B(r - r_G(t_B))$$

(1)

where $u(r)$ is the input wave amplitude at position $r$, $\delta_A(r)$ and $\delta_B(r)$ are the Gaussian-like functions that approximate a large value in circular and horizontal elliptical areas with the center $r = 0$, respectively, and $b_1$ and $b_2$ are scattering coefficients in the weld defect at position $r_W(t_B)$ and on the back surface at position $r_G(t_B)$, respectively. Note that $r_W(t_B)$ and $r_G(t_B)$ are constant before LC because there is no temperature change within the specimen.

Subsequently, the top surface of the specimen is locally cooled by a cooling spray, which can cool the specimen to 218 K if the heat transfer coefficient is high ($\sim 10^7 \text{ W m}^{-2} \text{K}^{-1}$). The vicinity of the top surface thermally contracts, and thereby, tensile thermal stress is applied to the closed crack by a principle similar to that of a three-point bending test. Here, the stress applied can be controlled by varying the GP temperature since the stress depends on the temperature difference $\Delta T$ between the top surface and the crack area. By selecting an appropriate GP temperature, the closed crack tip is opened. As a result, the crack tip is imaged by the PA (Fig. 2(b)), where the image intensity at time $t$ after the onset of LC is given by

$$I(r, t) = b_1 u(r_W(t)) \delta_A(r - r_W(t)) + b_2 u(r_G(t)) \delta_B(r - r_G(t))$$
where $c(t)$ is the scattering coefficient in the closed crack tip at position $r_c$. Here $c(t)$ is the function of $t$ because it is 0 before LC and increases by the application of the thermal stress induced by GPLC. Note that $r_c(t)$, $r_b(t)$, and $r_0(t)$ are also the function of $t$ because the wave velocity of the specimen changes depending on the temperature while PA images are created on the basis of the assumption of a constant wave velocity.

On the other hand, the PA image shown in Fig. 1(b) visualizes not only the crack but also the other linear scatterers, as shown in Fig. 2(e). Here the presence of the scatterers is not negligible, $r_c(t)$, $r_b(t)$, and $r_0(t)$ slightly change depending on $t$. Therefore, in applying the conventional subtraction method that subtracts the PA image at $t_B$ from that at $t > 0$, not only the crack but also the ghosts remain in the subtracted image, as shown in Fig. 2(d). Here the image intensity is given by

$$I(r, t) = c(t)u(r_c(t))\delta_3(r - r_c(t)) + b_1u(r_W(t))\delta_3(r - r_w(t)) + b_2u(r_B(t))\delta_3(r - r_B(t)),$$

where $c(t)$ is the scattering coefficient in the closed crack tip at position $r_c$. Here $c(t)$ is the function of $t$ because it is 0 before LC and increases by the application of the thermal stress induced by GPLC. Note that $r_c(t)$, $r_b(t)$, and $r_0(t)$ are also the function of $t$ because the wave velocity of the specimen changes depending on the temperature while PA images are created on the basis of the assumption of a constant wave velocity.

To solve this problem, we propose the STIS method, as an option of LDPA, of subtracting a PA image from that obtained before a short time interval. Here we focused on that the change in $c(t)$ is faster than that in the average wave velocity during GPLC. Therefore, by selecting an appropriate short time interval $\Delta t$, $r(t - \Delta t)$ can be approximated as $r(t)$. Thus, by subtracting PA image (Fig. 2(c)) at $t - \Delta t$ from that (Fig. 2(d)) at $t$, only the crack can be extracted with canceling the other linear scatterers, as shown in Fig. 2(e). Here the subtracted image is given by

$$\Delta I_2(r) = I(r, t) - I(r, t - \Delta t) = c(t)u(r_c(t))\delta_3(r - r_c(t)) - c(t - \Delta t)u(r_c(t - \Delta t))\delta_3(r - r_c(t - \Delta t)) + b_1u(r_W(t))\delta_3(r - r_w(t)) - b_1u(r_W(t - \Delta t))\delta_3(r - r_w(t - \Delta t)),$$

where $u(r(t))$ is not sensitive to a slight change in $r$.

To demonstrate the aforementioned principle, a compact tension (CT) specimen made of aluminum alloy (A7075) was used, as shown in Fig. 3. The shape of the CT specimen was based on ASTM-E399. The distance between the notch and the top surface was 40 mm. To form closed cracks, the fatigue conditions used were as follows: a maximum stress intensity factor of 9.0 MPa$\cdot$m$^{1/2}$ and a minimum stress intensity factor of 0.2 MPa$\cdot$m$^{1/2}$. The crack was extended to a depth of approximately 10 mm on the side surface (Fig. 3(b)) after 76,000 cycles. It was confirmed in Ref. 20 that the crack was tightly closed and the depth was 11.3 mm.

3. Specimen

To demonstrate the aforementioned principle, a compact tension (CT) specimen made of aluminum alloy (A7075) was used, as shown in Fig. 3. The shape of the CT specimen was based on ASTM-E399. The distance between the notch and the top surface was 40 mm. To form closed cracks, the fatigue conditions used were as follows: a maximum stress intensity factor of 9.0 MPa$\cdot$m$^{1/2}$ and a minimum stress intensity factor of 0.2 MPa$\cdot$m$^{1/2}$. The crack was extended to a depth of approximately 10 mm on the side surface (Fig. 3(b)) after 76,000 cycles. It was confirmed in Ref. 20 that the crack was tightly closed and the depth was 11.3 mm.

4. Results

4.1 Imaging of closed cracks by GPLC

The experimental configuration is shown in Fig. 4.20) To image the crack, a PA was used. The PZT array (manufactured by Imasonic) used has 32 elements with a center frequency of 5 MHz, where the element size and pitch are 10 and 0.5 mm, respectively. The array was driven by a phased array hardware (produced by KrautKramer). The excitation voltage was a pulse wave with a voltage of 100 V. The sampling rate was 50 MS/s. Shift-and-sum was done with 1 mm step in depth and 1° step in angle, following delay laws.24) To apply thermal stress to the crack, GPLC was used. The GP temperature was selected to be 323 K, and the specimen was heated by a hot plate. Subsequently, as illustrated in Fig. 4, the vicinity of the top surface was locally cooled from the area of the top surface confined by the acrylic lid by two cooling sprays (HFC-125a) for 10 s. During cooling, the crack was monitored by the PA in real time.

The snapshots of the PA images monitored before and after the onset of LC are shown in Fig. 5, where the time step was selected to be 1 s to examine the change in PA images with $t$ in detail. Before LC, the notches $N_T$, $N_L$, and $N_B$ were imaged, whereas the crack was not imaged in Fig. 5(a). This
shows that the crack was closed. Here, $N_T$, $N_L$, and $N_R$ denote the top, left side and right side of notch, respectively, as defined in Fig. 5(q).

At $t = 1$ s just after the start of LC at $t = 0$ s, the crack was still not imaged as shown in Fig. 5(b). This shows that the thermal stress was insufficient for opening the crack because of the very short cooling time. Note that the notch response at $N_L$ was stronger than that at $N_R$ in Fig. 5(a). Considering the geometric relationship between the array and the notch, it is conceivable that the scattered wave field from $N_L$ and $N_R$ mainly exists in the left and right side of the crack, respectively, because the array was positioned on the left side of top surface as shown in Fig. 4. Therefore, the array can receive a stronger scattered waves from $N_L$ than those from $N_R$.

On the other hands, the crack was clearly imaged between $t = 2$ and $t = 12$ s, as shown in Figs. 5(c)–5(m). The maximum crack depth was 11.3 mm in Figs. 5(e)–5(g) between $t = 4$ and $t = 6$ s. Importantly, the crack depth measured is the same as the actual value of 11.3 mm. This shows that GPLC is significantly effective in opening a tightly closed crack. Then, as the cooling time increased at $t \geq 7$ s, the crack appeared at shallower part, as shown in Figs. 5(h)–5(m). Finally, it diminished at $t \geq 13$ s, as shown in Figs. 5(n)–5(p). This is because the thermal stress

Fig. 4 Experimental configuration. A CT specimen with a closed crack extending from a notch is placed on a hot plate for GP. The top surface confined by an acrylic lid is cooled by two cooling sprays (HFC-132a) from the left and right sides. Here, the two commercially available cooling sprays are used for rapid cooling to 218 K over the confined area. The area surrounded by the dotted line is imaged by the PA in real time while applying thermal stress.

Fig. 5 Snapshots of PA images with global preheating (323 K) and local cooling and schematic illustration: (a) PA image before local cooling, (b)–(p) PA images between $t = 1$ s and $t = 15$ s at 1 s step, respectively, and (q) schematic of imaging area. The PA images of (b)–(p) were obtained after finishing the cooling, since the cooling was finished at $t = 10$ s. The dotted lines in (a) represent the geometrics of notch and crack.
decreased since the temperature distribution within the specimen gradually became uniform. This also suggests that the short cooling time of approximately 4 s is sufficient in opening the tightly closed crack for the specimen.

4.2 High-selectivity imaging of crack by LDPA

To achieve a high selectivity of the closed crack, we applied LDPA to the PA images (Fig. 5), as shown in Figs. 6 and 7. First, using a conventional method\(^{20}\) based on eq. (3), we subtracted the PA image (Fig. 5(a)) before LC from those (Figs. 5(b)–5(p)) after the onset of LC, as shown in Fig. 6. Although the response at \(N_L\) was much stronger than that at the crack in the PA images (Fig. 5) before LDPA, the response at \(N_L\) was reduced and the change in the crack response was extracted in Fig. 6, where \(N_L\) is a strong linear scatterer unrelated to the crack opening/closing behavior.

Note that there is a fully white area around \(N_L\). This is because the responses at \(N_L\) in the PA images were clipped due to the limitation of dynamic range of the phased-array hardware, where we selected a high gain to visualize the response of crack. Between \(t = 2\) and \(t = 8\) s, the increase in the response at the crack and the decrease in the response at the root of crack were clearly observed as red and blue parts, respectively, in Figs. 6(b)–6(h). However, the responses at \(N_L\) were still observed in the subtracted images (Figs. 6(m)–6(o)) between \(t = 13\) and \(t = 15\) s, although it seems that there was no change in the PA images (Figs. 5(n)–5(p)) between \(t = 13\) and \(t = 15\) s. This is the ghost, which was schematically illustrated in Fig. 2(d), generated by the effect of the change in the wave velocity depending on the temperature. The ghost degraded the selectivity of closed cracks, which could be the problem in the case of Figs. 1(a) and 1(b). Note that the upper and lower parts of the ghost were the red and blue, respectively. This can be understood by the following. It is reasonable that the average wave velocity between \(t = 13\) and \(t = 15\) s was higher than that before LC because the average temperature of the specimen between \(t = 13\) and \(t = 15\) s is lower than that before LC. On the other hand, the PA images were created on the basis of assumption of a constant longitudinal wave velocity. Therefore, the response at \(N_L\) appeared at higher positions in the PA images (Figs. 5(n)–5(p)) between \(t = 13\) and \(t = 15\) s than in that (Fig. 5(a)) before LC.

To solve this problem, we applied the STIS method, of subtracting between the PA images with a short time interval \(\Delta t\), to the PA images. On the basis of eq. (5), the subtracted images were calculated, as shown in Fig. 7, where \(\Delta t = 0.5\) s. As a result, we succeeded in extracting the time...
evolution of change in crack response. In Fig. 7(c), only the crack tip was visualized with eliminating the response of notch. Also note that the response at \( N_L \) was successfully eliminated in Figs. 7(m)–7(o) between \( t = 13 \) and \( t = 15 \) s. This is because the average temperature at \( t - \Delta t \) were almost the same as that at \( t \). Note that this enables us to precisely track the time evolution of the crack changes. Thus, we demonstrated that the proposed method is useful in enhancing the selectivity of closed cracks.

5. Discussions

To validate the proposed method, we quantitatively examined the intensity of ghosts in Figs. 6(n) and 7(n) at \( t = 14 \) s, respectively. As a ghost, the intensity of the response at \( N_L \), which is a strong linear scatterer unrelated to the crack opening/closing behavior, was selected. The intensity was calculated as the mean intensity values in the region surrounded by dotted square in Figs. 6(n) and 7(n). As a result, the intensity at \( N_L \) was marked by 21.3 dB, as shown in Fig. 8. Thus, we demonstrated that the combination of GPLC and the STIS method of LDPA is significantly useful in reducing the ghosts due to the change in the temperature of the specimens.

Furthermore, we quantitatively examined the selectivity of cracks for the other linear scatterers in Figs. 5(e), 6(c), and 7(c), respectively. As a measure of the selectivity, the intensity ratio of cracks to objects other than cracks is defined as

\[
S = \frac{I_c}{I_l},
\]

where \( I_c \) is the intensity of the response at the crack tip and \( I_l \) is the intensity of the response at \( N_L \). These were calculated as the mean intensity values in the region surrounded by dotted square in Figs. 5(e), 6(c), and 7(c). As a result of LDPA, \( S \) was markedly enhanced by 15.3 and 26.8 dB in Figs. 6(c) and 7(c), respectively, as shown in Fig. 9. Thus, we demonstrated that the STIS method can achieve a higher selectivity than the conventional subtraction method of LDPA.

In this study, we focused on reducing the ghosts due to the change in the temperature of specimens. On the other hand, the STIS method is very useful in precisely tracking the crack behavior. For instance, we found that the crack was mostly unchanged between Figs. 7(e) and 7(h), whereas the change was large in Figs. 7(a)–7(c), 7(j) and 7(k). It was found that the different parts were opened between Figs. 7(a) and 7(c).

Furthermore, in this study, we selected \( \Delta t = 0.5 \) s as an appropriate condition for this specimen and GPLC condition.
For a shorter $\Delta t$ than 0.5 s, the ghosts due to wave velocity change could be reduced in subtracted images, whereas only the smaller change in crack responses could be obtained. On the other hand, for a longer $\Delta t$ than 0.5 s, the larger change in crack responses could be obtained in subtracted images, whereas the ghosts due to wave velocity change would increase. Note that a longer $\Delta t$ could overlook the short time change in crack responses than $\Delta t$. Thus, it can be expected that an appropriate $\Delta t$ depends on the material, the characteristics of closed crack, GPLC conditions, etc. In future works, we will perform the further examination of the $\Delta t$ dependence of subtracted images not only in this specimen but also in the other specimens.

The change in wave velocity of specimens due to GPLC can be influenced on the crack depth measurement. However, this is not significantly influential on the crack depth measurement in this study, since the maximum crack depth was observed at a relatively short time $t = 4 \text{ s}$. On the other hand, the longer cooling time can be needed depending on the material and size of specimens. In such a case, not only the application of the STIS method but also the calibration of wave velocity would be useful in achieving a very high measurement accuracy of crack depth.

The formulation in Section 2 is based on intensity subtraction, providing information of the increase or decrease in the intensity. On the other hand, the application of waveform subtraction is also conceivable. This provides the variance of phase changes as well as amplitude changes, although it does not provide the increase or decrease in the extent of change. However, this is very sensitive to the temperature change since this is able to extract the phase change. To reduce the temperature effect, the intensity subtraction is better than the waveform subtraction.

6. Conclusions

To achieve a high selectivity of closed cracks in ultrasonic imaging, we proposed a short time interval subtraction (STIS) method to subtract a phased array (PA) image from that obtained before a short time interval. It is an option of the load difference phased array (LDPA). After confirming the crack opening capability of the global preheating and local cooling (GPLC), we applied STIS to the PA images. As a result, only the crack responses were successfully extracted in the subtracted image, with eliminating the responses of linear scatterers, whereas the conventional subtraction method of subtracting a PA image obtained before a start of LC from that after the start of LC could not eliminate the responses of linear scatterers. Thus, we demonstrated that the combination of the STIS in LDPA and GPLC is very useful in achieving a high-selectivity imaging of closed cracks.

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