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Imaging of Closed Cracks in Coarse-Grained Materials by Nonlinear Ultrasonic Phased Array

粗大結晶粒材料の閉じたき裂の非線形超音波フェーズドアレイ映像

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1. Introduction

In nuclear power plants, crack depth measurement is indispensable to ensure their safety and reliability. To this end, there are two difficulties that are crack closure and coarse grains. Crack closure causes the underestimation or miss-detection because the ultrasound transmits through the closed cracks. Coarse grains cause strong linear ultrasonic scatterings, which can hide the crack tip responses because crack tip responses are generally weak.

For crack closure, we have developed two closed-crack imaging methods. The first is subharmonic phased array for crack evaluation (SPACE), based on subharmonic generation and phased array algorithm with frequency filtering.[1] The second is global preheating and local cooling (GPLC)[2-4] that temporarily opens closed cracks by the application of tensile thermal stress. GPLC is a very simple but still powerful. For coarse grains, a load difference phased array (LDPA)[5] would be effective. LDPA is a method of subtracting phased array images between different external loads. The fundamental performance was demonstrated in the fatigue crack specimen in terms of improving the selectivity of the closed crack for the notch response, which is a linear scattering source. However, it has yet to be demonstrated in actual coarse-grained material.

The objective of this study is to demonstrate that the combination of GPLC and LDPA is useful in accurately measuring closed crack depth in coarse-grained material.

2. Principle of GPLC and LDPA

A schematic of the combination of GPLC and LDPA is shown in **Fig. 1**, where the linear phased array (PA) imaging of coarse-grained material with a crack with a closed tip is considered. After globally preheating the specimen, the open part of crack, the back surface, and the coarse grains are imaged by PA (Fig. 1(a)), whereas the closed crack tip is not imaged because ultrasound transmits through the closed crack tip. Subsequently, the top

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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 sufficiently high ($\sim 10^5$ W·m^{-2}·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 readily controlled by varying the global preheating (GP) temperature. As a result, the crack tip is imaged by PA (Fig. 1(b)).

However, the selectivity of closed cracks for the other linear scatterers can be considerably low, since the coarse grains responses can hide the crack tip responses due to the weakness of the crack tip response. This can lead to the misjudgment of the crack tip response and/or the deterioration of the measurement accuracy of crack depth. To overcome this difficulty, we focused on that by applying GPLC, the closed crack tip response increases, whereas the responses of the other linear scatterers are not changed. In LDPA, by subtracting the PA images before and after GPLC, only the crack can be selectively imaged while canceling the other linear scatterers, as illustrated in Fig. 1(c).

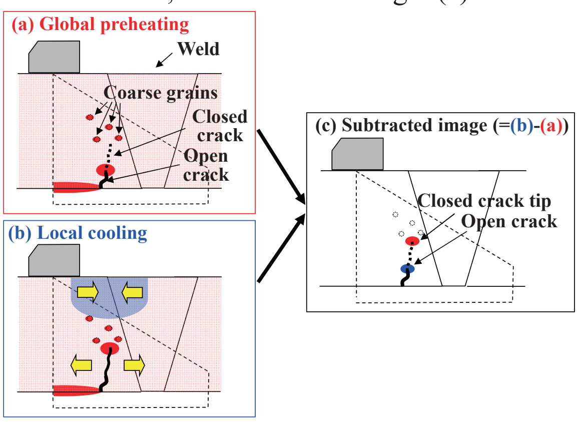

Fig. 1　Schematic illustration of GPLC and LDPA.

3. Experimental Configurations

To demonstrate the aforementioned principle, a fatigue crack was extended in a compact tension (CT) specimen made of stainless steel (SUS316L) with coarse grains (**Fig. 2**) of which the maximum size was approximately 150 μm. The fatigue conditions were selected as follows. A maximum stress intensity factor K_{max} was gradually decreased from 18.6 MPa· $m^{1/2}$ to 8.6 MPa· $m^{1/2}$ by 1 MPa· $m^{1/2}$ per 1 mm extension of crack depth.

The experimental configuration is shown in Fig. 2. The PZT array used has 32 elements (5 MHz, 0.5 mm pitch). Each element of the array was excited by a pulse with a voltage of 100 V. Delay-and-sum was done with 1 mm step in depth and 1 $^{\circ}$ step in angle. In GPLC, the specimen was globally preheated to 323 K by a hot plate. Subsequently, 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 GPLC, the crack was monitored by the PA in real time.

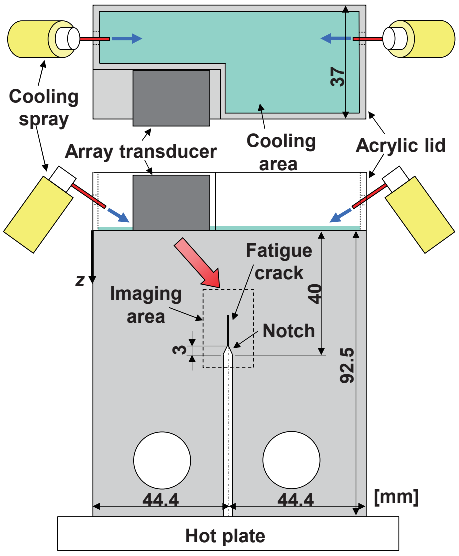

Fig. 2 Experimental configurations.

4. Experimental Results

The snapshots of the PA images monitored during GPLC are shown in **Fig. 3**. After GP and before LC, the notches and coarse grains were imaged, whereas the crack was not imaged in Fig. 3(a). This shows that the crack was tightly closed. At more than t=2 s after the onset of LC at t=0 s, the crack was imaged. As t increased, the crack depth increased. The maximum crack depth was tentatively measured to be 13.3 mm, as shown in Fig. 3(b). The identification of crack tip response, however, was difficult because of the responses of multiple coarse grains over the entire imaging area, as expected. Therefore, the LDPA was applied to the PA images (Figs. 3(a) and 3(b)) obtained at t=0 s and t=10 s. As a result, the linear scatterers were successfully cancelled in the LDPA image (Fig. 3(c)) and the selectivity of crack tip response was markedly improved. The crack depth was measured to be 15.0 mm, which was larger than that measured in the PA image (Fig. 3(b)). Also note that the crack depth was almost the same as that confirmed in the experiment using a mechanical tensile stress. Thus, it was demonstrated that in coarse-grained material, the combination of GPLC and LDPA is useful in enhancing the selectivity of crack in ultrasonic imaging and realizing high measurement accuracy of crack depth.

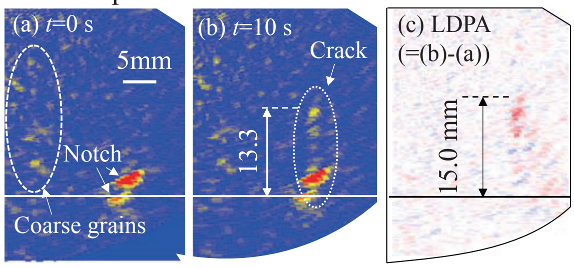

Fig. 3 PA images during GPLC and LDPA image.

5. Conclusions

To verify the combination of GPLC and LDPA in coarse-grained materials, it was applied to the closed fatigue crack specimen made of coarse-grained stainless steel. Although the closed crack was not imaged before applying GPLC, the crack was visualized by linear phased array by applying GPLC. The identification of crack tip response, however, was difficult because of the responses of multiple coarse grains over the entire imaging area. Then, LDPA was applied to the PA images before and after applying GPLC. As a result, the selectivity of crack tip response was markedly improved by canceling the coarse grain responses and the crack depth was accurately measured. Thus, the combination of GPLC and LDPA was verified in actual coarse-grained material.

Acknowledgements

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References

1. Y. Ohara, T. Mihara, R. Sasaki, T. Ogata, S. Yamamoto, Y. Kishimoto, and K. Yamanaka: Appl. Phys. Lett., **90** (2007) 011902.
2. Y. Ohara, K. Takahashi, S. Murai, and K. Yamanaka: Appl. Phys. Lett., **103** (2013) 031917.
3. Y. Ohara, K. Takahashi, K. Jinno, and K. Yamanaka: Mater. Trans., **55** (2014) 1003.
4. K. Takahashi, K. Jinno, Y. Ohara, and K. Yamanaka: Jpn. J. App. Phys., **53** (2014) 07KC20.
5. Y. Ohara, S. Horinouchi, M. Hashimoto, Y. Shintaku, and K. Yamanaka: Ultrasonics, **51** (2011) 661.