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Detection of small cracks using high- T_c SQUIDs in an unshielded environment

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Abstract

In this study, we utilized high- T_c rf SQUIDs to detect microcracks in metallic samples in an unshielded environment. The environmental noise in the SQUID was suppressed by using a first-order electronic gradiometer. The samples under investigation were excited by ac magnetic fields applied by a differential excitation coil. A technique utilizing the differential defect field was adopted to analyse the defect field from the crack. It was found that the crack is detectable for the crack width down to micrometres. In addition, the defect field is not a function of the crack width when it is much less than the size of the excitation coil. Finally, the SQUID nondestructive evaluation (NDE) system that was built was also applied to detect small cracks due to fatigue.

1. Introduction

Since the noise of the high- T_c SQUID was much lower than that of the other magnetic sensors operated at room temperature, the nondestructive evaluation (NDE) with the high- T_c SQUID was expected to have a better performance than that of the traditional eddy-current NDE [1]. Many remarkable studies with different excitation schemes for the SQUID-based eddy-current NDE were reported [2–5]. Among these, the method using the differential excitation coil has achieved spatial resolution down to the millimetre range [3–5]. But it was a challenge to use the method for the quantitative flaw determination because the differential excitation field resulted in a difficult eddy-current problem. In our previous study on a crack in the millimetre range, the magnitude of the defect field was found to be a function of both the crack depth and crack height, while the phase of the defect field was shown to be a function of crack depth only. As a result, the linear relation between the phase and the crack depth is unique in determining the depth of a millimetre crack [6]. Moreover, we also discovered that the behaviour of the magnitude and the phase of the differential defect fields are also similar to the previous results, but in more advanced conditions, the accompanied offset field can be eliminated by using this differential method [7]. Therefore, it is suggested that the differential method is a reliable and powerful tool. The detection of sub-millimetre

cracks by using the high- T_c SQUID NDE system has been reported [5]. However, it is not clear whether the quantitative analysis with the differential defect field [7] can be applied to the micrometre crack.

In this study, the NDE system that was built was used to study the relationship between the defect fields and the crack width in the micrometre range. In addition, the development of the fatigue crack is also an interesting point in this report.

2. Experimental details

In the previous paper, we studied the depth dependence of the defect field by using a high- T_c dc SQUID with a small cylindrical shield to enhance the signal-to-noise ratio. It was shown that the proper excitation frequency for evaluating the depth of the crack in the aluminum sample is several hundred Hz [6]. Although the noise level of the high- T_c rf SQUIDs [8] was almost as good as that of the high- T_c dc SQUIDs [9] at the working frequency range, the high- T_c rf SQUID operated with high slew-rate electronics is more suitable for measurements in an unshielded environment. The rf SQUIDs used in this report were the commercialized high- T_c SQUIDs from the Juelicher SQUID company in Germany.

The SQUID-based NDE system consisting of such high- T_c rf SQUIDs and relevant electronics is shown in figure 1. The system was similar to the one reported in [6] with the

Figure 1. SQUID-based eddy-current nondestructive evaluation system (NDE).

Figure 2. The noise level of the rf SQUID magnetometer and the first-order gradiometer measured in the unshielded environment.

high- T_c dc SQUID magnetometer replaced by the first-order rf SQUID electronic gradiometer, which consists of a sensor SQUID magnetometer and a reference SQUID magnetometer arranged axially with the baseline of 12 cm. To avoid signals from ambient eddy currents, the SQUIDS were mounted inside the dewar made of non-metallic fiberglass. In the NDE system, a double-D excitation coil was used to minimize the excitation field in the sensor SQUID. The distance from the sensor SQUID magnetometer to the excitation coil adhered to the dewar bottom is 20 mm, and the distance from the excitation coil to the sample surface is 1–3 mm. The plane of the SQUIDS is parallel to that of the excitation coil. A two-dimensional scan was performed by mounting the sample onto a computer controlled X–Y table.

It is well known that the noise level of the first-order electronic SQUID gradiometer is lower than that of the SQUID magnetometer because the common-mode environmental noise is cancelled out electronically. The noise of the rf SQUID magnetometer and that of the first-order rf SQUID gradiometer measured in the open laboratory is given in figure 2. With the electronic gradiometer, the environmental noise was reduced in a broad frequency range since the signal distortion of the rf SQUID electronics is negligible within the bandwidth limit. In addition, as the magnetic signal detected by the reference

Figure 3. Defect fields for the crack width from 10 μm to 2 mm, (a) with the 2.8 cm excitation coil, and (b) with the 0.3 cm excitation coil. The excitation frequency is 400 Hz.

SQUID magnetometer is negligible in the NDE experiments, the electronic rf SQUID gradiometer functions as a single rf SQUID magnetometer with the noise level reduced by almost one order of magnitude as shown in figure 2. Thus, the first-order rf SQUID gradiometer exhibited a higher field sensitivity and hence is adopted in the study.

In order to investigate the relationship between the defect field and the width of the micro crack, an artificial micro crack with an adjustable width was designed. The width of the crack was defined by the distance between the edge surfaces of two 1.5 mm thick aluminum plates. The crack width was adjusted by means of two screws pushing the aluminum plates. In order to achieve the smallest crack width, the edge surfaces of the plates were mechanically polished to the roughness much less than 10 μm . Thus, it was possible to have a crack width less than 10 μm with this technique.

3. Results and discussion

The defect fields over the crack for the crack width from 10 μm to 2 mm with the 2.8 cm and the 0.3 cm excitation coils were shown in figures 3(a) and (b) respectively. With the 2.8 cm excitation coil, it was found that neither of the in-phase or the quadrature components of the defect field overlap when the crack width was varied from 10 μm up to 2 mm. Namely, both the phase and magnitude of the defect field were independent of the crack width below 2 mm. This observation confirms the result reported previously for the millimetre crack [6]. The reason that the defect fields are insensitive to the crack width was attributed to the broad region of the eddy-current distribution as the size of the excitation coil was much greater than the width of the crack. Hence, the change in width does not affect the eddy-current distribution effectively. When the diameter of the excitation coil, e.g. 0.3 cm, was not much greater than the crack width, the defect field altered slightly as the crack width was changed as shown in figure 3(b).

Since the behaviour of the defect field due to a micro crack was similar to that due to a millimetre crack with the 2.8 cm excitation coil, the corresponding relations such as the

Figure 4. (a) Formation of the fatigue crack in the 0.5 mm thick aluminum plate; (b) photograph of the fatigue crack after four cycles of bending.

linear phase–depth relation [6] should also be valid. Thus, it was suitable to apply the NDE system to study the micro cracks quantitatively, e.g. the depth and the height of the fatigue crack. The fatigue crack to be detected in this study was caused by bending an aluminum plate for several cycles as shown in figure 4(a). The aluminum plate shown in the figure was 70 mm × 10 mm × 0.5 mm in dimension. The outer and the inner surface of the plate were defined with respect to the direction of the bend, and the crack height was the vertical size of the crack. The development of the fatigue crack was examined by using an optical microscope. After four cycles of bending, the photograph of the fatigue crack on the outer surface of the plate was shown in figure 4(b). It was found that a main crack developed across the aluminum plate with some minor deformations around the main crack. These cracks must have resulted from the tensile force during the bending.

In order to use the linear behaviour of the phase–depth relation [6, 7] to analyse the fatigue crack, the 0.5 mm aluminum plate was placed on a 9.5 mm aluminum slab in the depth evaluation, as shown in figure 5(a). The aluminum

Figure 5. (a) Evaluation of fatigue crack by using the differential excitation coil; (b) in-phase and quadrature phase defect fields for zero to seven cycles of bending.

plate was flattened carefully after bending so that the air gap between the aluminum plate and the aluminum slab is less than 0.1 mm. In this way, the distance L , which was measured from the upper surface of the overall stack to the middle of the crack height, can be found by using the phase–depth relation. As long as L was measured, the crack height can be calculated from the relation: crack height = $2 \times (0.5 - L)$ mm. The defect fields over the fatigue crack after various cycles of bending were plotted in figure 5(b). According to the experiment, the in-phase and the quadrature components of the defect field almost remained the same if the aluminum plate was bent less than four cycles, whereas the defect field rose apparently as a continuing bend. When the plate had undergone seven cycles, it broke into two pieces. It was noted that the air gap between the aluminum plate and the aluminum slab near the location of the crack did not contribute to the defect field since the size of the air gap did not change from the first cycle to the seventh cycle.

Although the development of the fatigue crack was observable by the growth of the defect fields, the offset signal still interfered in the judgement of the depth in the real case. Therefore, the defect field was differentiated with respect to the horizontal distance to obtain the differential defect field. In figure 6(a), the in-phase and the quadrature components of the

Figure 6. (a) In-phase and quadrature components of the differential defect fields for zero to seven cycles of bending; (b) magnitude of the differential defect field at $x = 0$ for three to seven cycles of bending.

differential defect field B_{diff} for zero to seven cycles of bending are shown. Both the in-phase and the quadrature components of the offset field in figure 5(b) were diminished to obtain a rather symmetric curve with respect to $x = 0$, at which the crack was located. In addition, for zero to three cycles of bending, the differential defect fields were virtually zero. Hence, the contribution from the offset field to the differential defect field was negligible. In contrast to the defect fields given in figure 5(b), the offset signal was obvious, which would affect the calculation of the magnitude and the phase of the defect field. Therefore, the differential defect field has proved to be more useful and accurate than the defect in probing the crack.

For bending cycles of more than four, significant variations in the differential defect fields occurred and were observed in figure 6(b). For more cycles of bending, B_{diff} increased rapidly until the aluminum plate broke into two pieces. Since the variation in the magnitude of the defect field is related to the crack depth and the crack height [6], the

Figure 7. (a) Differential phase over the fatigue crack; (b) differential phase at $x = 0$ for four to seven cycles of bending. The crack depth L was calculated according to the phase-depth relation at 400 Hz as shown in the inset.

abrupt increase in B_{diff} indicates that the fatigue crack grew rapidly after the fourth cycle.

In order to determine the crack height quantitatively, the phases of the differential defect field ϕ_{diff} were analysed for four to seven cycles of bending as shown in figure 7. For zero to three cycles of bending, the differential phases ϕ_{diff} were not meaningful because the differential defect field was virtually zero, which would induce great uncertainty in determining the phase. The differential phases ϕ_{diff} at various horizontal positions for four to seven cycles of bending are shown in figure 7(a). It was found that the differential phase changed gradually near $x = 0$, and varied rapidly when $x \approx \pm D/4$, where D ($=2.8$ cm) is the diameter of the excitation coil. For the positions away from the crack, the differential phase changed slowly again. The spatial variation of the differential phase constituted a U-shaped curve near $x = 0$, which is a useful indicator for the buried flaw. The position of the crack was indicated by the symmetric axis of the U-shaped curve, and the differential phase at $x = 0$ corresponds to the distance of the crack measured from the top surface of the aluminum stack [7]. Notably, the value of ϕ_{diff} near $x = 0$ was found to become a little more negative after more cycles of bending for the plate.

The differential phase ϕ_{diff} at the position of the fatigue crack ($x = 0$) for four to seven cycles of bending was shown in figure 7(b). In the inset, the phase–depth relation for a buried crack was plotted according to [7]. The crack depth L shown in the figure was calculated from ϕ_{diff} by using the relation shown in the inset. It was found that ϕ_{diff} varied from 36° to 42° , which corresponds to the change of the crack height from 0.48 mm to 0.26 mm when the number of cycles increased from four to seven. This means that the fatigue crack grew up until the crack height was equal to the thickness of the 0.5 mm thick aluminum plate, i.e. the plate broke. This behaviour was in good agreement with the observed development of the fatigue crack.

4. Conclusion

In conclusion, we have constructed a NDE system by using an rf SQUID electronic gradiometer. Our system can sense the crack width down to micrometre range and potentially to the sub-micron range, but cannot identify the dimension of the width, which is much less than the size of the excitation coil. The utilization of the differential defect field can increase the reliability of the NDE system because of the elimination of the offset field accompanying the defect field. The height and depth of the fatigue crack can be detected by using the differential defect field. Hence, it is practical and convenient to apply the SQUID-based NDE system to detect the small cracks due to fatigue.

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