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SQUID NDE for *in situ* inspection of copper heat exchanger tubes

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Abstract

An eddy-current-based SQUID NDE system was constructed for *in situ* inspection of copper heat exchanger tubes using an HTS SQUID gradiometer and a Helmholtz-type-coil inducer. Thin copper tubes of 6.35 mm in diameter and 0.8 mm in thickness were selected from products as specimens. Artificial flaws of 100 μm in width, 15–25 mm in length and 10–50 μm in depth were made on the surfaces of the tubes. The tubes were moved at a velocity of 1.6–32 m min^{-1} by a motor through the Helmholtz-type coil, which generated an excitation field of 10 μT at 3 kHz. The SQUID NDE system could detect an anomalous magnetic response due to a flaw of 10 μm in depth on the tube moving at 32 m min^{-1}.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In order to extract better performance, copper heat exchange tubes used, for example, in air conditioning have had a thickness of less than 1 mm. Thus, even a shallow flaw of 20–30 μm in depth on the surface of a tube, which accidentally happened in the manufacturing process of the tube, can be a potential cause of tube breakage when the tube is bent or flared in post-processes. Eddy current testing (ECT) has been employed to detect defects in metallic tubes in tube factories [1, 2]. However, the sensitivity of commercial ECT systems is not enough to detect such shallow flaws. Thus, a more sensitive NDE technique, which can be applied in tube factories, is much demanded by manufacturers and users of these tubes.

The HTS SQUID is an uncontested sensitive sensor with magnetic field resolution of several tens of fT/Hz$^{1/2}$ [3]. Taking advantage of the great sensitivity between nearly DC and several hundred kHz, the SQUID NDE has already shown some significant results in the detection of small defects in metallic materials and structures [4–6]. In particular, for a SQUID NDE application on copper heat exchanger tubes, the NDE technique must have not only high sensitivity but also robustness against noise and practical usability, since the tube factories will be electromagnetically noisy and the tubes are moved at high speed (more than 100 m min^{-1}) in the manufacturing process.

To meet these requests, we constructed an eddy-current-based SQUID NDE prototype system for *in situ* inspection on copper heat exchanger tubes using an HTS SQUID gradiometer, which is expected to cancel the environmental magnetic noise. In this paper, the details of the system and demonstration of detection of surface flaws of a few tens of μm in depth on the copper tubes moving at up to 32 m min^{-1} are described.

2. SQUID NDE prototype system for copper tubes

2.1. Principle of the SQUID NDE on tubes

In the manufacturing process of copper heat exchanger tubes, flaws that occur on the tubes are lengthened along the axis of the tube. To detect such long and shallow flaws, a Helmholtz-type coil composed of two field coils is a suitable inducer because it induces eddy current circulating around the circumference of the tube (perpendicular to the axis of the tube) when the

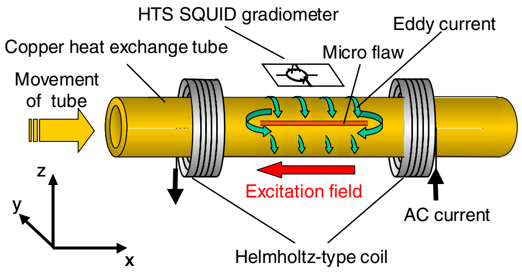

Figure 1. Principle of the SQUID NDE for a copper tube.

tube passes through the inducer. A schematic image of the SQUID NDE on a copper tube with a flaw is illustrated in figure 1. The copper heat exchanger tube under test is moved through a Helmholtz-type coil, which applies an excitation field to the specimen. An HTS SQUID gradiometer, which is located in the middle of the Helmholtz-type coil and above the tube, measures the magnetic anomaly generated by the eddy current, which is disturbed by the micro-flaw on the surface of the tube.

2.2. Details of the system

The SQUID NDE prototype system for copper heat exchanger tubes is composed of an HTS SQUID gradiometer with electronics, a cryostat, a Helmholtz-type coil with position adjuster, a current supplier, a lock-in amplifier, an electric motor, and a PC. Figure 2 shows a schematic illustration of the system. The HTS SQUID planar gradiometer has a differential pick-up coil composed of two rectangular coils. The sizes of the single coil and the baseline length of the gradiometer are 2.88 mm $\times$ 3.6 mm and 3.6 mm, respectively. The details of the gradiometer are given elsewhere [7]. We used an FRP cryostat that can hold liquid nitrogen for 6–7 h. The Helmholtz-type coil was set in the polymeric position adjuster, which is used to minimize the excitation magnetic flux coupled to the SQUID. The turn number and dimensions of each field coil are 1000 and 50 mm in diameter and 45 mm in length, respectively. The field coils are separated with a distance of 36 mm between each coil end while aligning the axis. The electric motor can move a tube on a rail at 32 m min^{-1} (maximum). The magnetic flux noise of the system measured was about 60 $\mu\phi_0$ Hz$^{-1/2}$ from 10 Hz to 5 kHz. The corresponding field gradient noise is about 6 pT cm^{-1} Hz$^{-1/2}$.

3. Specimens

Copper heat exchanger tubes that had artificial shallow flaws with various depths on the surfaces were prepared as specimens. These tubes were selected from commercial products. The dimensions of all the tubes are 6.35 mm in outer diameter, 0.8 mm in thickness and 300 mm in length. The dimensions of the flaws are 100 μm in width and 15 mm in length, and the depths of the flaws are 50, and 30 μm, respectively. A shallowest flaw of 100 μm in width, 25 mm in length and 10 μm in depth was also made on the same kind of tube. The flaws were made using an electric discharge machine.

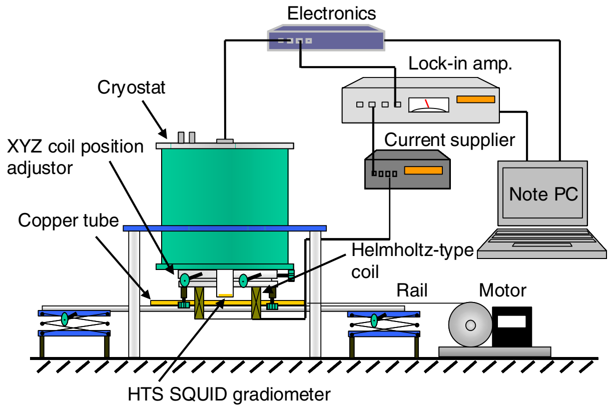

Figure 2. Schematic diagram of the SQUID NDE system.

4. Measurements and results

4.1. Measurements

We evaluated the detection ability of the SQUID NDE system by inspecting the flaws on the copper heat exchanger tube specimens. A sinusoidal current of 3 kHz was supplied to the Helmholtz-type coil to generate an excitation field. The magnetic flux density B_x (parallel to the axis of the tube under test) at the middle of the two field coils was about 10 μT. The tube specimens were moved through the inducer at a velocity of 1.6–32 m min^{-1}. The flaws were set to be on top of the tube specimens with a lift-off distance 1.5 mm between the HTS SQUID gradiometer and the tube top. The HTS SQUID gradiometer measured the field gradient in the x-direction of the vertical magnetic field component, $\mathrm{d}B_z/\mathrm{d}x$ (see figure 1), with a sampling frequency of 100–1000 Hz.

4.2. Results

The experimental results on the tube specimens with 50, 30, and 10 μm-depth flaws using an excitation field of 10 μT at 3 kHz while moving the tube at 1.6 m min^{-1} are shown in figures 3(a)–(c), respectively. In each figure, a schematic view of the tube specimen is depicted together for the reference of the position of each flaw. Anomalous magnetic responses due to the micro flaws appear above and around the flaws. Even the 10 μm-depth flaw was successfully detected by the system, which other traditional NDE techniques may fail to detect. The signal peak-to-peak amplitude due to a flaw decreases as the depth of a flaw becomes shallow, which is roughly proportional to the depth of a flaw. However, this relationship between the flaw depth and signal amplitude differs from the previous results, where the signal amplitude was proportional to the square of the flaw depth [7]. In previous experiments on the same kind of specimen, the specimens were moved stepwise and accurately by another stepper-motor. On the other hand, in this study, the specimens were continuously moved on the rail, in which a little gap between the rail and the specimen holder was given to enable the specimen to move quickly. The gap may cause the flaw on the specimen not to pass just under the centre of the SQUID so that the signal response could be smaller than the case in which the flaw passed under the centre.

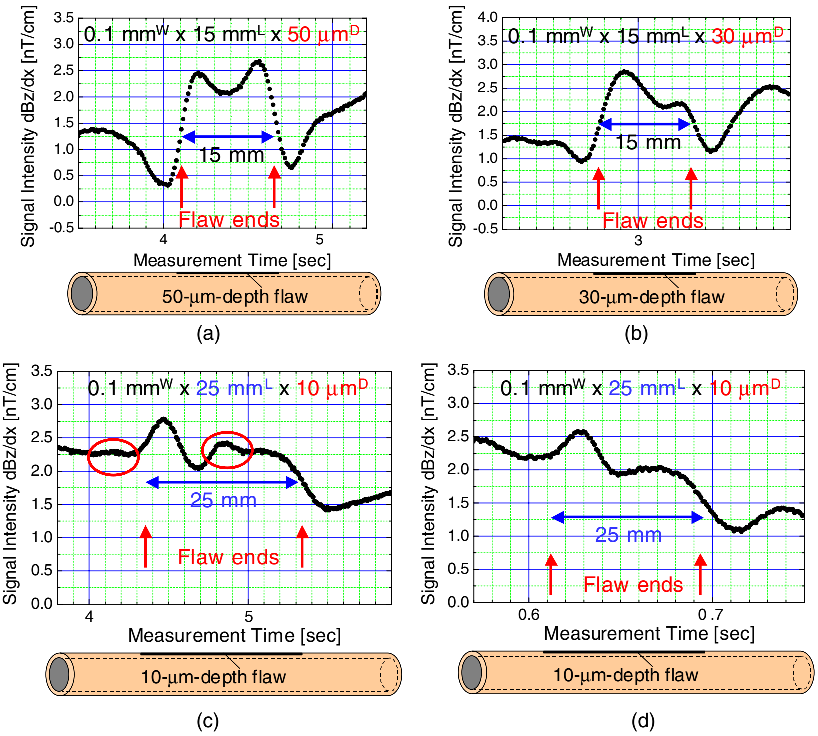

Figure 3. Measurement results on (a) 50 μm-depth flaw, (b) 30 μm-depth flaw, (c) 10 μm-depth flaw and (d) 10 μm-depth flaw. In the measurement on (d), the specimen was moved at 32 m min^{-1}, while in the other cases ((a)–(c)) the specimens were moved at 1.6 m min^{-1}. The circles in (c) indicate the noises that may be caused by the vibration of the tube being moved slowly.

Figure 3(d) shows the results on the tube with the 10 μm-depth flaw moving a bit faster, at 32 m min^{-1}. Almost the same waveform as figure 3(c) was measured. The noise in figure 3(d) is somewhat smaller than in figure 3(c) (indicated by the circles) although the moving speed in the case of (d) was faster than in (c). That may be due to a little bit larger vibration of the specimen caused by the friction between the rail and the specimen holder when the specimen was moved slowly. It is necessary to make an improvement on the system to suppress the tube vibration to within at least 10 μm.

5. Conclusions

An eddy-current-based SQUID NDE prototype system was constructed for *in situ* inspection of copper heat exchanger tubes using an HTS SQUID gradiometer and a Helmholtz-type coil. With an excitation field of 10 μT at 3 kHz, the SQUID NDE system could detect a magnetic response due to a 10 μm-depth flaw on a tube of 6.35 mm in outer diameter, 0.8 mm in thickness while moving the tube at 32 m min^{-1}. An improvement on the system that should suppress the tube vibration will be made. The system will be brought into a tube factory, and then routine inspection on quickly moving tubes in the manufacturing process will be tested.

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