Multi-channel High-$T_c$ SQUID Detection System for Metallic Contaminants

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Abstract

Finding ultra-small metallic contaminants is a big issue for manufacturers of lithium-ion batteries nowadays. Therefore, we have developed high-$T_c$ SQUID systems for detection of such fine magnetic metallic contaminants. In this paper, we constructed an eight channel high-$T_c$ SQUID gradiometer system for inspection of a sheet electrode of a lithium ion battery with width of about 70 mm. By this system, a small iron ball of about 30 μm in diameter was successfully detected. It is shown that this system has a detectable range of 70 mm in width. These results suggest that the system is a promising tool for the detection of the contaminants in lithium ion batteries.

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1. Introduction

Recently, in the fields of leading-edge industry and the food processing, fine metallic contaminants mixed in the products cause the serious problems. Therefore, the metallic contaminant detection process becomes indispensable on the production lines. In such detection on the lines, precise detection technology is demanded. As the conventional methods, induction coil or x-ray computed tomography scanner have been employed. However, the induction coils are lacking in the sensitivity, and the x-ray computed tomography scanners are lacking in the time resolution. Thus, it is difficult by them to detect
the metallic contaminants of less than 100 μm in diameter on the product lines [1-4]. However, there is an urgent need for precision industry products such as lithium-ion electrodes, in which 10μm–order size magnetic contaminants cause some faults. Furthermore, the matrix of industrial products can be magnetized and magnetic signals from the matrix are sometimes sufficiently large to mask signals from contaminants in many cases. Thus, we have developed a detection system employing high-\(T_c\) SQUID gradiometers and horizontal magnetization of such magnetic products in a longitudinal direction [5-7]. Since this system was the prototype which used a few SQUIDs, the detectable area was restricted. In order to detect the electrode with a width of several tens mm on the production line, it is necessary to arrange more sensors to cover the full width of the electrode. In this work, we developed a multi-channel contaminant detection system, in which eight SQUIDs are arranged two-dimensionally. The system characteristics were evaluated.

2. Detection system for metallic contaminants

2.1. Principle of detection of contaminant

A principle of the detection of the contaminant is shown in Fig. 1 (a). The contaminant detection method using SQUIDs require to magnetize a specimen with a permanent magnet to detect remnant magnetization of the contaminant. Since lithium ion electrodes often contain magnetic materials, they can be also magnetized. In order to distinguish the magnetization of the specimen and that of the contaminant, we employed the horizontal magnetization method in this work. By using this method, the magnetization field from the specimen appears only from the both ends of it as shown in Figs.1. On the other hand, the contaminant generates a local magnetization field near by the contaminant. By detecting the local magnetic field by a SQUID gradiometer, the signals from the matrix and that from the central contaminant are separable as shown in Fig. 1 (b).

![Diagram](image)

**Fig. 1.** (a) Diagram of detection method for fine metallic contaminant; (b) Signal from metallic contaminant in magnetic matrix measured by high-\(T_c\) SQUID gradiometer
2.2. Detection system

Fig. 2 (a) shows the multi-channel high-$T_c$ SQUID detection system for metallic contaminants, which we have developed. In the system, microscopic cryostat, in which 8-channel SQUID array was mounted, is installed in the double-layer magnetic shield for reduction of environmental magnetic noise. In addition to the cryostat, the system is composed of an electronics for 8 channels, a belt conveyor for movement of a specimen and a PC to store data. The dimensions (length × width × height) of the entire system are 2000 mm × 750 mm × 1550 mm. This contaminant detection system is aimed to be used in manufacturing process of lithium ion electrodes and the likes, thus the belt conveyor conveys a sample continuously at the speed of about 100 mm/sec. Eight high-$T_c$ SQUID gradiometers were mounted at the tips of the sapphire rods using silver paint as adhesive. The rods are connected to a copper tank in the cryostat. As shown in Fig. 2 (b), the SQUIDs were arranged with intervals of 28 mm in the lateral direction and 18 mm in the longitudinal direction between the centres of the gradiometers for inspection of a full width of the lithium-ion electrode foil of about 70 mm. By arranging the SQUIDs in two rows, the second series of the 4 SQUIDs can cover the area between the front series of the 4 SQUIDs. Liquid nitrogen is poured in the tank in the cryostat and the SQUID gradiometers are cooled at near 77 K through the sapphire rods. The averaged white noise level of all the SQUID gradiometers was 25 $\mu\phi$/Hz$^{1/2}$ at 100 Hz. The magnetized specimen passes under the eight SQUIDs, and the remnant magnetization from the contaminant is measured. We record the outputs of the SQUIDs with a low pass filter with the cut-off frequency of 20 Hz and high pass filter with the cut-off frequency of 0.2 Hz.

![Fig. 2. (a) Block diagram of contaminant detection system; (b) Arrangement of SQUIDs on tips of sapphire rods](image-url)
3. Characterization of system

3.1. Detection of contaminant on magnetic material

An electrode foil of a lithium-ion battery that we target is often made of magnetic materials. Therefore, we prepared a brass plate specimen as a magnetic material, on which an iron ball of 75 \( \mu \text{m} \) in diameter was fixed. The size of the brass plate used as a magnetic matrix is 100 mm \( \times \) 10 mm \( \times \) 1 mm. The brass specimen was inspected by the SQUID system. The sample was magnetized horizontally by the permanent magnet of about 0.5 T, and it was transported under the SQUID array by the belt conveyor. The remnant magnetization from the edges of the brass specimen was measured at 7.35 s and 8.37 s when each edge of the specimen passed under the SQUID, which positioned nearest to the specimen, as shown in Fig. 3. On the other hand, a larger signal was detected at 7.85 s when the contaminant passed under the SQUID. From the result, it was demonstrated that it is possible to discriminate the contaminant signal from the matrix signal by this system.

![Fig. 3. Detection result of a contaminant on magnetic material](image)

3.2. Relationship between diameter and signal of contaminant

Magnetic signals from contaminants with different diameters were measured with the developed contaminant detection system. Fine iron (S50C) balls with diameters of 27-95 \( \mu \text{m} \) were prepared as contaminants. Each iron ball was set on a glass plate. The lift-off distance between the contaminant and the SQUID array was about 2-2.5 mm. The results are shown in Fig. 4 (a). In this experiment, one of the eight SQUID gradiometers was used. The relationship between measured signal amplitude and diameter of contaminant is shown in Fig. 4 (b). As shown in the figure, signal amplitude of contaminant was approximately proportional to the square of diameter of contaminant. The averaged peak-to-peak noise in the measurements was about 1.5 m\( \Phi_0 \). Actually, a signal to noise ratio (S/N) necessary for proper detection of contaminant is 3 or more. From the result in Fig. 4 (b), it is suggested that the system can detect a iron ball of 20 \( \mu \text{m} \) in diameter with the S/N of 3.

![Fig. 4. (a) Measurement results of iron balls with different diameters; (b) Peak-to-peak amplitude as a function of diameter of iron ball.](image)
3.3 Detectable area of system

On the belt conveyer of 100 mm in width, the detectable range, in which the contaminant can be detected with the 8-channel SQUID array, was measured. The slide glass with an iron ball of 50 μm in diameter was used as a specimen as shown in Fig. 5 (a). While changing the initial position of the specimen in the range of y=-35 mm to +40 mm with an interval of 2 mm, magnetic signals from the iron ball were measured by the SQUID array. The results are shown in Fig. 5 (b). In the measurements, the output of a SQUID, which was nearest to the path of the transported iron ball, was selectively recorded, and all the data were put in the single graph. When the contaminant passed the centre of each sensor, the signal became the maximum. The peak amplitudes of the outputs are a bit irregular due to imperfection of the arrangement of the SQUID array although the deviations of the amplitudes are acceptable. The valleys, where the signal strength is low, exists between the signals of each neighbouring channel. However, there was no measurement area where the outputs were zero. The averaged noise level in the experiments was about 2 mΦ₀. Considering the S/N of 3 necessary for the proper detection of the iron ball of φ50 μm, it can be said that the detectable area of the system was about 70 mm.

Fig. 5. (a) Experimental set up for measurement of detectable area; (b) Detectable area of the system using iron ball of 50μm in diameter

4. Conclusion

We developed the multi-channel contaminant detection system using 8-channel high-\( T_c \) SQUID gradiometer array and the horizontal magnetization method for the industrial products such as the lithium ion electrodes. It was shown that this system has a capability to detect an iron ball of about 20 μm in diameter with the S/N of 3 or more at a lift-off of about 2 mm. It was demonstrated that the detectable range on the belt conveyer was about 70mm in the case of the iron ball of 50 μm in diameter, thanks to the two-dimensionally arranged SQUID array. The iron ball with a diameter of 75 μm on the brass plate was detected with enough S/N while separating the signal from the ball from the signals from the plate by use of the gradiometers and the horizontal magnetization. The success of the eight-channel system proposed in this paper encourages us to apply this system to a production line on site.
References


