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High-T_c SQUID Application for Roll to Roll Metallic Contaminant Detector

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Abstract

A sensitive eight-channel high-Tc Superconducting Interference Device (SQUID) detection system for magnetic contaminant in a lithium ion battery anode was developed. Finding ultra-small metallic foreign matter is an important issue for a manufacturer because metallic contaminants carry the risk of an internal short. When contamination occurs, the manufacturer of the product suffers a great loss from recalling the tainted product. Metallic particles with outer dimensions smaller than 100 microns cannot be detected using a conventional X-ray imaging system. Therefore, a highly sensitive detection system for small foreign matter is required. We have already developed a detection system based on a single-channel SQUID gradiometer and horizontal magnetization. For practical use, the detection width of the system should be increased to at least 65 mm by employing multiple sensors. In this paper, we present an 8-ch high-Tc SQUID roll-to-roll system for inspecting a lithium-ion battery anode with a width of 65 mm. A special microscopic type of a cryostat was developed upon which eight SQUID gradiometers were mounted. As a result, small iron particles of 35 microns on a real lithium-ion battery anode with a width of 70 mm were successfully detected. This system is practical for the detection of contaminants in a lithium ion battery anode sheet.

Keywords : SQUID, Magnetic Contaminant

I. Introduction

During the manufacturing of industrial products such as lithium-ion (Li-ion) batteries, the possibility remains that contaminants may be accidentally mixed with the products. Examples of these contaminants are small metal chips from row materials or processing machinery. The industry requirement is to find metallic particles that have a diameter greater than 50 μm. However, particles smaller than 100 μm cannot be detected by X-ray imaging, which is commonly used as the inspection method. Therefore, a highly sensitive detection system for small contaminants is required. Some SQUID

detection systems for detecting contaminants in food have been developed [1-4]. One of these systems is commonly available at present [5]. However, in most cases, the matrix of industrial products is magnetized, and the magnetic signal from the matrix is sometimes sufficiently large to mask the signals from the contaminants. Thus, we have proposed the use of a planar gradiometer and horizontal magnetization of the sample prior to measurement. This combination reduces the large signal from the matrix and clarifies the signal from the metallic contaminants [6-8]. For practical use, it

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is important to increase the detection width of the system by employing multiple sensors with a wide sensing area so that the system can inspect sheets with a width of approximately 65 mm, which is the size of the commonly used cylindrical Li-ion battery "18650." Here, we describe a roll-to-roll detection system based on an eight-channel (8-ch) high-T_c SQUID gradiometer.

II. Detection System

A block diagram of the roll-to-roll detection system is shown in Fig. 1. The magnet horizontally magnetizes the metallic contaminants and the matrix of the test object. The SQUID gradiometer detects these remanent magnetic fluxes. If they are magnetized vertically because a matrix such as a lithium-ion battery electrode is magnetized, a signal from the contaminant is hidden by that from the matrix and cannot be detected [6]. However, this problem is solved in the system employing horizontal magnetization. In addition, utilizing a SQUID gradiometer to measure the magnetic field gradient would minimize the effect of the remanent field from the product edges.

The system consists of a permanent magnet, feeder, winder, magnetically shielded box, and SQUID-mounted cryostat, which is fabricated from aluminum alloy and works as an electromagnetic shield. The flux density of the permanent magnet is 1.3 T over the width of 100 mm. The sheet material for inspection moves from the left to the right and passes through a permanent magnet before detection. The remanent magnetic flux from a metallic contaminant in the sheet is detected by the SQUID gradiometers when the sheet passes below the sensor. The feeder and the winder are driven by stepping motors and are controlled with tension. The system's nominal maximum speed is 100 m/min, and it has no anti-meander controller. This winding system can accept a sheet with a width of 100 mm. The detection unit including a shield and a cryostat was independent from the magnet and the driving components in order to protect them from mechanical vibration. The dimensions (length × width × height) of the entire system are 2200 mm × 700 mm × 1380 mm.

The liquid nitrogen (LN_2) cryostat used for maintaining the temperature of the eight SQUID gradiometers at 77 K was custom designed. A photograph of the cryostat is shown in Fig. 2. The size (D × W × H) of the cryostat was 240 mm × 210 mm × 415 mm. The outer jacket of the cryostat was fabricated from aluminum alloy, and the LN_2 tank was fabricated from copper. The aluminum outer jacket works as an electromagnetic shield. The total volume of LN_2 was 1.1 L, and the required volume of LN_2 could be maintained for 14 h without refilling. This type of a cryostat is commonly called a SQUID-microscope-type cryostat. Eight cylindrical heat transfer rods (diameter: 15 mm) fabricated from sapphire were used. The SQUID gradiometers were located on the top of the rod with a chip carrier, which enabled the formation of electric connections with the SQUID chip. The distance between each SQUID gradiometer was 18 mm. The vacuum space was separated by a 0.5-mm-thick sapphire window. In this configuration, an object to be inspected could be placed as close as 1–2 mm to a SQUID gradiometer [9].

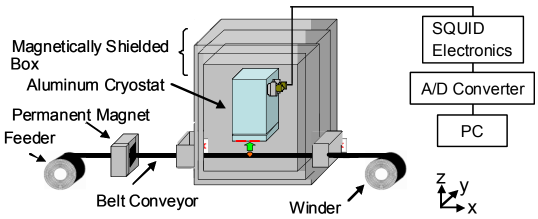

Fig. 1. Block diagram of the roll-to-roll contaminant detection system for lithium-ion battery anode sheet.

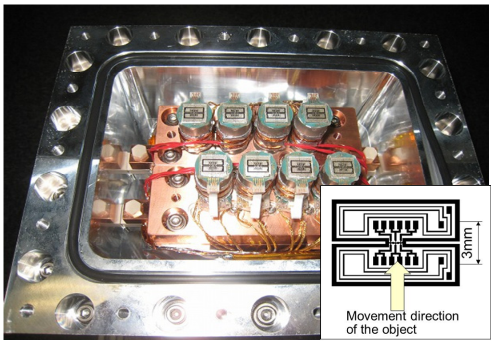

Fig. 2. Picture of custom-designed 8-channel cryostat. Inset indicates the schematic view of the gradiometer with movement direction of the object.

The design of a magnetically shielded box is important for increasing the total sensitivity of the system. We carefully designed the shield on the basis of the results of a finite-element model (FEM) simulated on a PC. We placed sleeves at the opening of the box, as this is known to be quite effective for obtaining a high shielding factor. We developed a three-layered shield box. The details of the design are described elsewhere [9, 10]. The inner and outer dimensions (length × width × height) were 380 mm × 300 mm × 524 mm and 630 mm × 480 mm × 704 mm, respectively. The thickness of the material was 2 mm. The measured shielding factors (*SF*) of the magnetically shielded box for each direction at 1 Hz were SF_x = 50,000, SF_y = 33,000, and SF_z = 25,000. These factors are sufficient for a practical system.

The SQUID gradiometers were fabricated from $YBa_2Cu_3O_{7-x}$ with a thickness of 200 nm that was sputter-deposited onto a $SrTiO_3$ bicrystal substrate and patterned by ion milling. The white noise level of the SQUID gradiometer was 20–30 $\mu\phi_0/Hz^{1/2}$ at 100 Hz. These values were 10 $\mu\phi_0/Hz^{1/2}$ higher than the values measured in LN_2 because of the relatively high temperature of the sapphire rod as compared to the LN_2 immersion. The size of the pickup loop is 8 mm × 3 mm for each. The base line of the gradiometer is 3 mm. The schematic view of the gradiometer with movement direction of the object is shown in the inset of the Fig. 2. For the SQUID driving electronics, we used a *PCI-1000* manufactured by *Star Cryoelectronics*. The SQUID driving electronics were modulation-type electronics with a bandwidth of 25 kHz. The signal passed through a high-pass filter (HPF) at a cutoff frequency of 0.5 Hz and a second-order low-pass filter (LPF) at a cutoff frequency of 100 Hz. The system was controlled by a PC. The software was developed by the authors, and a touch panel was employed as a user interface.

II. Evaluation

Small iron (S50C) balls with a diameter of 35–82 μm were prepared for the system evaluation. An iron ball was attached to the surface of the 100-μm-thick polyethylene sheet with Scotch tape. The position of the iron object was adjusted so that it passed under one of the eight planar SQUID gradiometers. The distance between a SQUID gradiometer and the object was approximately 3 mm. After the object was magnetized by the permanent magnet, its remanent field was measured using the SQUID gradiometer. The speed of the winder was 9 m/min. Real-time traces of the gradiometer output and the peak-to-peak values as a function of the ball diameter are shown in Fig. 3. The peak-to-peak values roughly scale with the cube of the diameter, specifically $D^{2.6}$. We believe that this is attributed to the anisotropy of magnetization. Further experiments are expected to clarify the reasons for this phenomenon.

In order to evaluate the sensitivity over the width of the eight gradiometers, we prepared iron (S50C) balls with diameters of 50 μm. The lift-off distance between the iron balls and the SQUID gradiometer was 3 mm. The position of the ball placed on the sheet was incremented in steps of 1 mm along the direction perpendicular to the sheet motion until the entire range from -32 mm to 44 mm was covered. The object was magnetized in the same manner, and the remanent signal from the iron ball was simultaneously detected by the eight SQUID gradiometers. The peak-to-peak values from ch 1 to ch 8 are plotted as a function of the offset distance in Fig. 4. The position of each peak is where each sensor is located. The noise level obtained from time traces was approximately 2 $m\phi_0$. If the detection width was defined such that the signal-to-noise ratio (S/N) was greater than 10

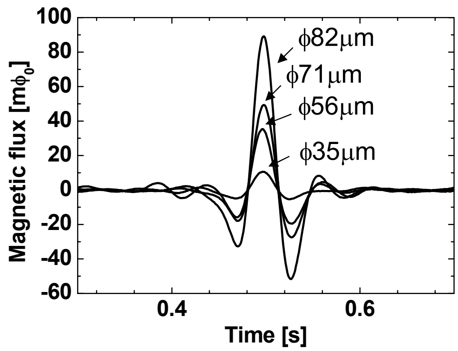

Fig. 3. Measured results of iron balls with different diameters using a SQUID gradiometer.

(corresponding to a signal level of 20 mϕ_0), the detection width of eight SQUID gradiometers was 70 mm. A range of 70 mm is large enough to inspect the anode sheet of the commonly used cylindrical Li-ion battery "18650."

Finally, a small iron ball on an active-material-coated anode sheet of a lithium-ion battery with a width of 65 mm was measured by the system. The diameters of the iron balls were ϕ35 μm, ϕ50 μm, and ϕ75 μm. The lift-off distance between the iron piece and the SQUID gradiometer was 3 mm. The results are shown in Fig. 5. The signals from the iron balls are quite clear and are separate from the signal from each edge of the sheet matrix. If there are metallic particles close to the edge, they can't be detected. But the length of the sheet is more than 2 m and these edges can be cut off.

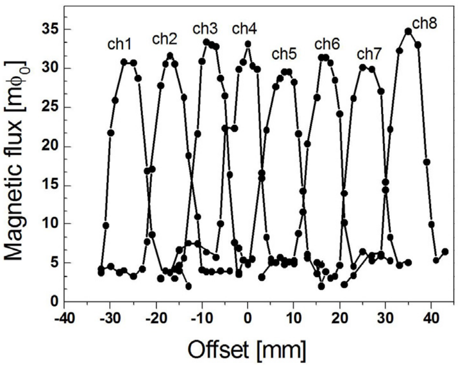

Fig. 4. Distribution of peak-to-peak values from an iron ball measured by eight gradiometers. The diameter of the iron ball was 50 μm.

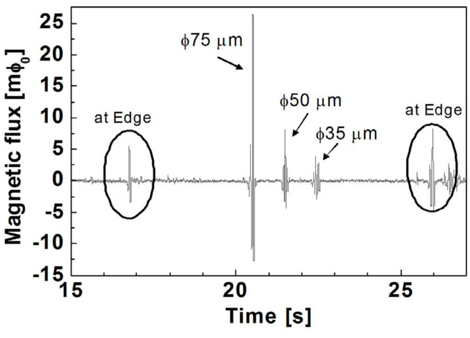

Fig. 5. Time trace of the signal for small iron balls with diameters of ϕ35 μm, ϕ50 μm, and ϕ75 μm on an active material coated anode sheet of a lithium-ion battery.

III. Conclusions

A roll-to-roll 8-ch high-T_c SQUID detection system for magnetic contaminants in a lithium-ion battery anode was developed. An iron ball with a diameter of ϕ35 μm was successfully measured using a single-channel SQUID gradiometer when the ball was placed at a distance of 3 mm from the gradiometer. When the winder speed was increased to 50 m/min, the signal intensities were the same as those at a low speed of 9 m/min. We also demonstrated that the 8-ch system can detect a ϕ50-μm iron ball within a range of 70 mm with an S/N ratio greater than 10. The range of 70 mm is large enough to inspect the anode sheet of the commonly used "18650" cylindrical Li-ion battery. The success of the eight-channel system proposed in this paper encourages us to apply this system to a production line.

References

[1] T. Nagaishi, H. Ota, K. Nishi, K. Kuwa, T. Fujita, and S. Tanaka, "First practical high-T_c SQUID system for the detection of magnetic foreign substances in commercial products", IEEE Transactions on Applied Superconductivity, vol. 17, pp. 800-803, 2007.

[2] S. Tanaka, H. Fujita, Y. Hatsukade, T. Nagaishi, K. Nishi, H. Ota, T. Otani, and S. Suzuki, "A food contaminant detection system based on high-T_c SQUIDs", Supercond. Sci. Technol, vol. 19, pp. S280-S283, 2006.

[3] H. J. Krause, G. I. Panaitov, N. Wolter, D. Lomparski, W. Zander, Y. Zhang, E. Oberdoerffer, D. Wollersheim, and W. Wilke, "Detection of magnetic contaminations in industrial products using HTS SQUIDs", IEEE Trans. on Appl. Supercond., vol. 15, pp. 729-732, 2005.

[4] M. Bick, P. Sullivan, D. L. Tilbrook, J. Du, B. Thorn, R. Binks, C. Sharman, K. E. Leslie, A. Hinsch, K. Macrae, and C. P. Foley, "A SQUID-based metal detector: comparison to coil and X-ray systems", Supercond. Sci. Technol., vol. 18, pp. 346-351, 2005.

[5] S. Tanaka, H. Fujita, Y. Hatsukade, T. Otani, S.

Suzuki, and T. Nagaishi, "A high-T_c SQUID micro-detector with a high performance magnetic shield for industrial products", Supercond. Sci. Technol., vol. 20, pp. S385-S388, 2007.

[6] S. Tanaka, T. Akai, Y. Hatsukade, T. Ohtani, Y. Ikeda, S. Suzuki, and H. A. K. Tanabe, "High T_c SQUID detection system for metallic contaminant in lithium ion battery", IEEE Trans. Magn., vol. 45, pp. 4510-4513, 2009.

[7] S. Tanaka, T. Akai, Y. Kitamura, Y. Hatsukade, T. Otani, and S. Suzuki, "Two-channel HTS SQUID gradiometer system for detection of metallic contaminants in lithium-ion battery", IEEE Trans. Appl. Supercond, vol. 21, pp. 432-435, 2011.

[8] S. Tanaka, Y. Kitamura, Y. Hatsukade, T. Ohtani, and S. Suzuki, "Metallic contaminant detection system using multi-channel high-T_c SQUIDs", Journal of Magnetism and Magnetic Materials, vol. 324, pp. 3487-3490, 2012.

[9] S. Tanaka, K. Matsuda, O. Yamazaki, M. Natsume, and H. Ota, "Development of high-T_c microscope with flux guide", Supercond. Sci. and Technology, vol. 15, pp. 146-149, 2002.

[10] K. Yamazaki, Y. Hatsukade, S. Tanaka, and A. Haga, "Shield duct to prevent magnetic field leakage through openings in double-layered magnetically shielded rooms", IEEE Trans. on Magnetics, vol. 44, pp. 4187-4190, 2008.