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Research on a haptic sensor made using MCF conductive rubber

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Abstract

To provide a new composite material having a high electrical sensitivity in the fields of robotics and sensing, a magnetic rubber having network-like magnetic clusters was developed by utilizing a magnetic compound fluid (MCF). MCF rubber with small deformations can provide an effective sensor. In this paper, we report many experiments in which changes of the MCF rubber's resistance were observed when the rubber was compressed and a deformation was generated; we then made a trial haptic sensor using the MCF conductive rubber and performed many experiments to observe changes of the electrical resistance of the sensor. The results of experiments showed that the proposed sensor made with MCF conductive rubber is useful for sensing small amounts of pressure or small deformations.

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

1. Introduction

The term 'functional fluid' is a general term referring to a kind of special fluid. Functional fluids have peculiar characteristics under magnetic or electric fields. There are two kinds of functional fluid responses to a magnetic field, and two types of functional fluids are defined by these responses, namely magnetic fluids (MFs) and MR fluids (MRFs). Applications of these fluids include their use as abrasives, dampers, etc. Many studies have been performed on the functional field [1, 2]. In engineering applications, however, MRFs and MFs also have some disadvantages. For example, in MFs the saturation magnetization is small, while it is difficult to treat MRFs hydrodynamically because of sedimentation of the fluid particles, which then act as a powder and become a big problem in engineering applications. To solve these problems, Professor Shimada developed a new functional fluid which responds to a magnetic field [3, 4]. This new fluid is known as MCF (magnetic compound fluid), and it possesses intermediate characteristics between MFs and MRFs. The MCF is a kind of colloid solution that contains ball-like iron particles on the order of about 1 μm and magnetite on the order of about 10 nm [5, 6]. The fluid contains magnetic clusters that consist of iron particles and magnetite particles. We discovered that the characteristics of MCF make it much more useful than MFs or MRFs for engineering applications. For instance, MCF abrasion, MCF dampers, MCF composite material, etc, can be listed [7]. In this study, we propose a new MCF composite material consisting of metal fine particles and silicon-oil rubber. To make the proposed MCF rubber, metal fine particles were compounded with MF, mixed with silicon-oil rubber, and then dried to become a solid rubber. We called the dried solid rubber 'MCF rubber'. If we dry the MCF rubber under a magnetic field, characteristics of the MCF rubber exhibit some changes. The metal fine particles included in the MCF composite material form network-like clusters under a magnetic field, and most of the clusters are formed along the direction of the magnetic field; therefore, the MCF rubber can conduct current flow and transfer heat well. In this research, we named the MCF composite material 'MCF conductive rubber'. In addition, we used the MCF conductive rubber to develop and trial-produce a touch sensor for use in a haptic robot. For this application, we must understand the conductivity of the MCF conductive rubber and, when the MCF rubber is compressed, the relations among the resistance, compressive force, and compressive contraction of the MCF rubber. In this study, we investigated the MCF conductive rubber's electrical characteristics, i.e. the relation among electrical resistance, compressive force, and compressive contraction, and then we produced a trial tip using MCF conductive rubber with the intended.

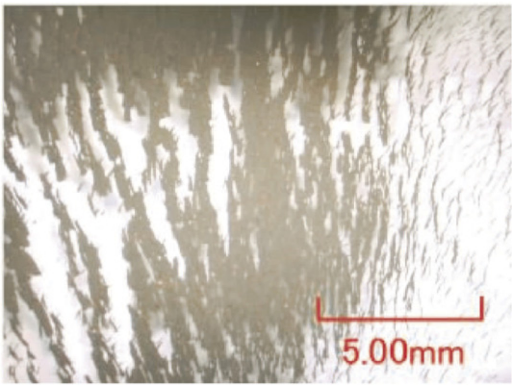

Figure 1. Photograph of magnetic clusters of MCF (Cu at 3 g, HQ at 3 g, MF at 4 g).

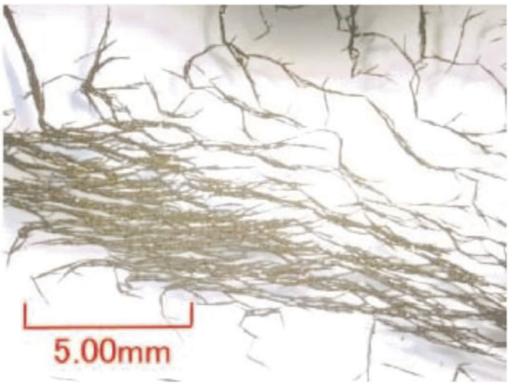

Figure 2. Photograph of magnetic clusters of MCF (Cu at 3 g, Ni at 3 g, MF at 4 g).

2. Electrical characteristics of MCF conductive rubber

2.1. About MCF

MCF conductive rubber has many magnetic clusters in a needle shape in the case where the MCF contains iron particles, HQ of 1.2 μm in diameter, and kerosene-based MF. To give the MCF rubber high electrical conductivity, Cu particles (length 8–10 μm) and Ni particles (length 3–7 μm) were used in the MCF compounded into the silicon-oil rubber. In the case of the MCF compounded with HQ and Cu, the shape of the HQ is spherical, and thus the magnetic clusters of MCF in the rubber have needle-like shapes, as shown in figure 1. In contrast, in the case in which Ni and Cu are used, the magnetic clusters of MCF in the rubber have network-like shapes, as shown in figure 2, because of the very twig-like shape of Cu and the remanent magnetization of Ni. The MCF rubber was dried under a magnetic field generated by two permanent magnets at about 5.44 kG.

2.2. Experiment methods

MCF rubber can conduct electric current flow only when the compounded MCF rubber is stiffened under a magnetic field. We observed the MCF conductive rubber's electrical characteristics and found that the larger the compressive force on the MCF rubber is, the lower the MCF conductive rubber's electrical resistance will be. It is therefore possible to use the MCF conductive rubber in a haptic sensor if the quantitative characteristics in addition to the qualitative characteristics of MCF rubber can be understood. In addition, we consider the MCF rubber to be most suitable for use in the haptic sensors in a welfare robot in human support systems in the future, because the MCF rubber is soft and is difficult to destroy. In this case, it is important to understand the change in electrical resistance when the MCF rubber is compressed or when a small deformation is generated. When MCF conductive rubber is compressed, it will become a conductor and can conduct current flow, and conversely, if the MCF is free, it will become an insulator like common rubber. Making use of these advantages of MCF conductive rubber, we experimentally produced a haptic sensor to sense a small pressure or deformation. To test the sensor's conducting ability, we performed many experiments. These experiments can be divided into two kinds: experiments in which the electrical resistance–compressive force relation of the MCF rubber was observed, and those in which the electrical resistance–compressive contraction relation of the MCF rubber was observed. To perform these experiments, the experimental device shown in figure 10 was assembled. Figure 3 shows the bench lathe used to exactly measure small deformations generated in the MCF conductive rubber when it is compressed by an external force. We fixed a load cell (LSM-50K-B, made by Minebea) to the bench lathe to measure the compressive force applied to the MCF rubber, then sandwiched the MCF rubber sample between two electrodes. The metal plate electrode on the right side was moved to the left to touch the load cell by turning the dial of the bench lathe; the metal plate electrode moved linearly along the rail direction of the bench lathe, the MCF conductive rubber sample was compressed, and a deformation (strain) was generated in the sample. The volume of deformation (strain) was measured precisely with the CCD laser displacement meter attached to the rail of the bench lathe (LK-G3000V, made by Keyence). In addition, we measured the voltage of the MCF conductive rubber on both sides and then calculated the electrical resistance value of the MCF conductive rubber using the following formula:

$$R_0 = 100/(5/V_0 - 1) \qquad (k1\ \mathrm{ON},\ k2\ \mathrm{Off}).$$

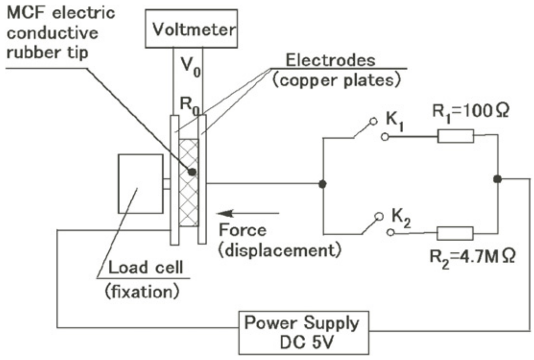

Figure 3. Schematic diagram of an experimental device.

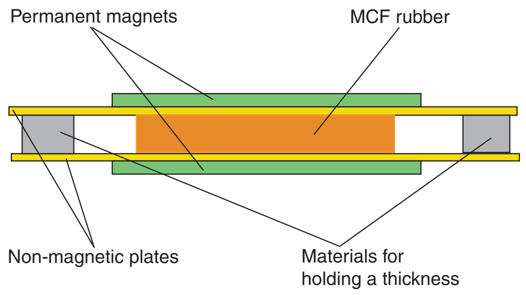

Figure 4. Schematic diagram of the production of MCF conductive rubber.

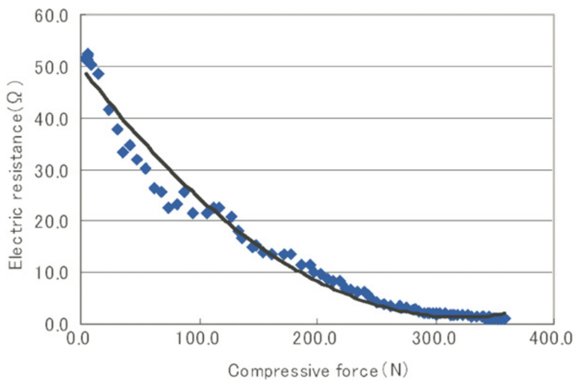

Figure 5. Electrical resistance–compressive force graph of the MCF conductive rubber.

To measure the electrical resistance of the MCF conductive rubber over a wide range, we also set up a high resistance branch circuit in which a 4.7 MΩ resistor is linked.

We mixed Ni(123) fine particles, Cu(MF-D2) fine particles and MF, then combined this mixture with silicon-oil rubber (SH9550). The mixture was poured between two non-magnetic thin plates and stiffened under a stronger magnetic field generated by magnets as shown in figure 4 for one day, to produce the MCF electric conductive rubber. In this research, we mixed the Ni(123), Cu(MF-D2) fine particles, MF fluid, and silicon-oil rubber (SH9550) in a 3:3:4:10 (weight rate) ratio to make a thin MCF conductive rubber film. Because the MCF rubber was stiffened under a strong magnetic field, many network-like clusters were formed with the fine particles in the MCF rubber, and the MCF rubber was transformed into a conductor. In addition, near the magnets, clusters were formed at a higher density. We used only the high density part in our experiments.

2.3. Relation of electrical resistance, compressive force, and compressive contraction in the MCF rubber

Figures 5 and 6 show the experiment results of a square MCF electric conductive rubber film of thickness 0.37 mm and dimensions 20 mm × 16 mm. Figure 5 shows the relation between electrical resistance and compressive force, and figure 6 shows the relation between electrical resistance and compressive contraction in the MCF rubber. When MCF rubber is compressed, the MCF electric conductive

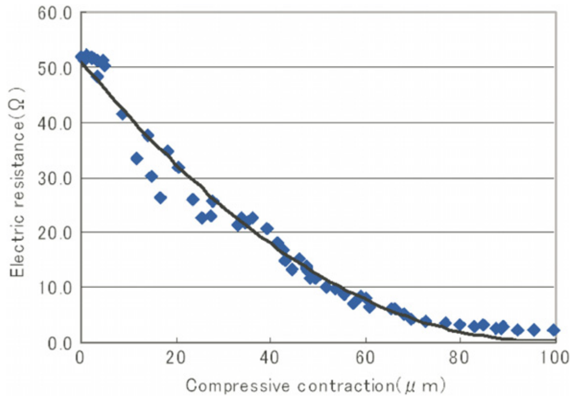

Figure 6. Electrical resistance–compressive contraction graph of the MCF conductive rubber.

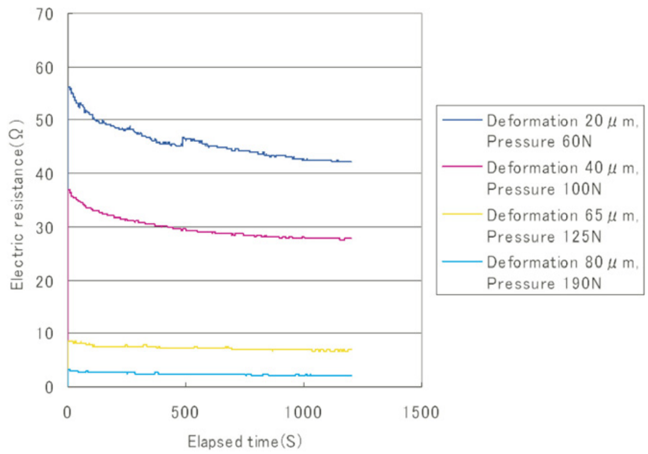

Figure 7. Electrical resistance–elapsed time graph of the MCF conductive rubber (while maintaining compressive force and contraction).

rubber's conductivity is increased. If the MCF rubber film is compressed and undergoes a contraction over about 50 μm, the conductivity improves and the electrical resistance decreases to the ohm order. This characteristic is sufficient for MCF to be used in a haptic sensor or a switching device.

2.4. Relation of electrical resistance and elapsed time in the MCF rubber

If MCF conductive rubber is pressed or if MCF rubber receives a compressive contraction, the electrical resistance of the MCF rubber initially decreases with elapsed time. However, after several minutes, the electrical resistance of the MCF rubber gradually becomes stable. The result is shown in figure 7. However, if an MCF rubber film is thin enough (less than 0.3 mm), then the changes of electrical resistance in the MCF conductive rubber will be limited to within a narrow range. Therefore, if a sufficiently thin MCF conductive rubber film is used to make a haptic sensor, the influence of elapsed time can be ignored.

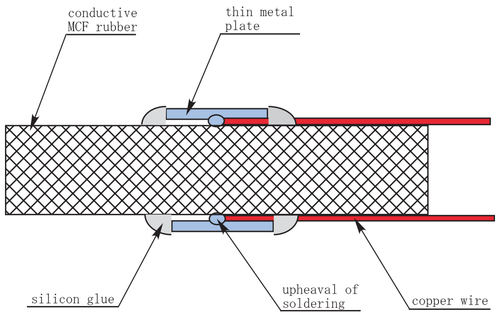

Figure 8. Schematic diagram of the structure of the haptic sensor tip made from MCF conductive rubber.

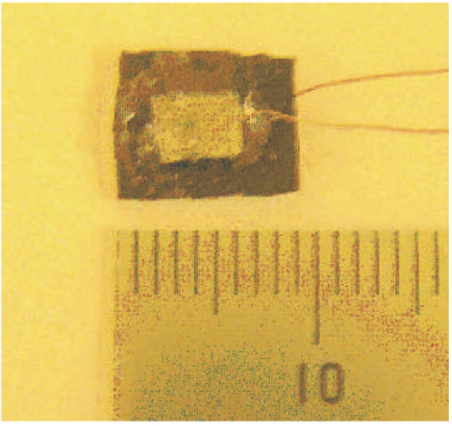

Figure 9. Photograph of the haptic sensor tip made from MCF conductive rubber.

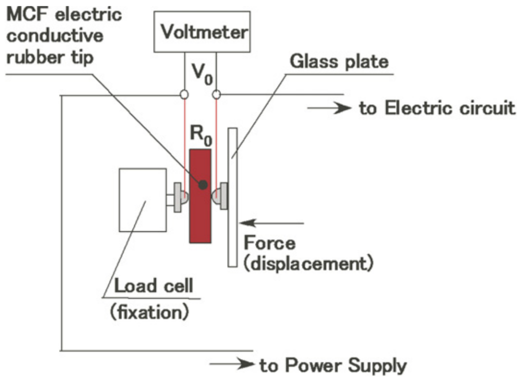

Figure 10. Principle of an experimental device for the haptic sensor tip made from MCF conductive rubber.

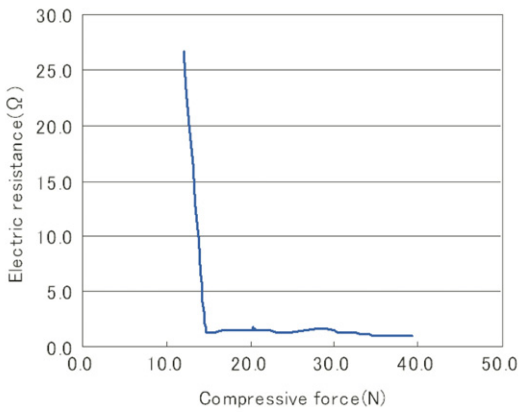

Figure 11. Electrical resistance–compressive force graph of the haptic sensor tip made from MCF conductive rubber.

3. Production of a trial touch sensor tip using a thin MCF electric conductive rubber film

3.1. How to make the trial sensor tip

We have made a trial haptic sensor tip using the MCF electric conductive rubber film. The manufacturing method and finished product (photograph) are shown in figures 8 and 9. Here we explain how to make the sensor tip (please see figure 8). First, we select a thin MCF conductive rubber film (the thickness is between 0.2 and 0.3 mm), then we attach extremely thin metal plate electrodes and extra-fine lead wires to the MCF conductive rubber film on both sides. The MCF rubber contacts only the upheaval from the soldering, and only the outside of the electrode is glued with silicon adhesive and is caused to adhere well. The upheaval parts of the solder on both sides of the MCF conductive rubber were located so that they faced each other. In this paper the tip sample dimensions are 0.6–0.8 mm in thickness and 10 mm × 10 mm in area, and a sample picture is shown in figure 9.

3.2. The electrical characteristics of the trial sensor tip

After the trial sensor tip was produced, we investigated the electrical characteristics of the sensor tip through many experiments in which we observed changes of its electrical resistance when the tip was pressed, as well as electrical resistance changes that occurred with elapsed time. Figure 10 shows a diagrammatical view of a device that measures the electrical resistance of the sensor tip. The bench lathe, load cell, laser displacement meter, measuring electric circuit and so on were used just as in figure 3, except with the points of difference described below.

(i) The facing metal plate electrodes were transformed into a small, thin plate.
(ii) The electrodes were made to touch the MCF rubber in a minute plane almost identical to a point touch.
(iii) The electrode was pushed to press the tip using a piece of glass plate from the firm insulation.

The relation between the electrical resistance in the trial sensor tip and the compressive force applied to the tip is shown in figure 11, and the relation between the electrical resistance and compressive contraction in the tip is shown in figure 12. As the compressive force grows large, the electrical resistance suddenly decreases, and when the compressive force is over 15 N or the compressive contraction is over 45 μm, the electrical resistance is close to a constant value (less than about 2 Ω). At this point, the sensor can transmit electric currents well; in other words, it has changed into a conductor from an insulator. Figure 13 shows the changes of the electrical

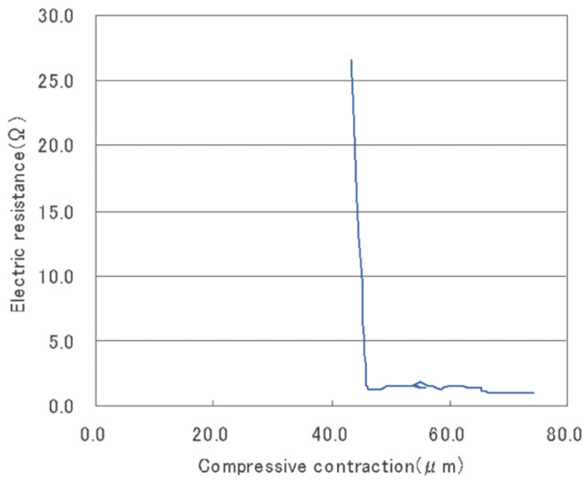

Figure 12. Electrical resistance–compressive contraction graph of the haptic sensor tip made from MCF conductive rubber.

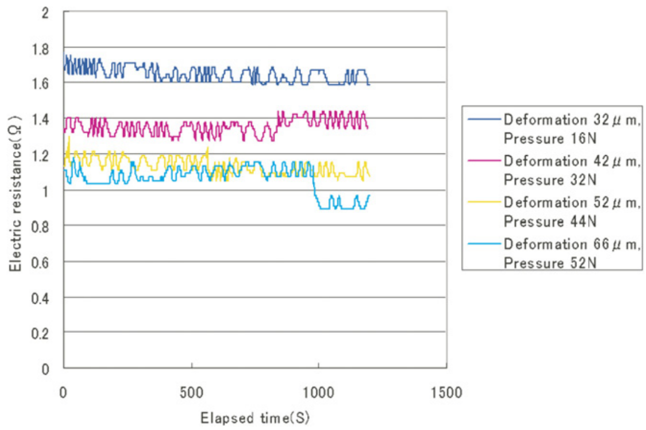

Figure 13. Electrical resistance–elapsed time graph of the haptic sensor tip made from MCF conductive rubber (while maintaining compressive force and contraction).

resistance with elapsed time when a constant compressive force or a constant contraction was maintained in the tip. It is different from figure 7 in that we decreased the area (top part of the upheaval of the soldering) of the electrodes touching the MCF conductive rubber; therefore, the electrical resistance becomes small. From this finding, it is clear that the electrical resistance of this sensor tip changes with the area and shape of the contact between the electrodes and the MCF rubber. Here, we studied mini-surface contact only. Although it is necessary to understand the influence of various shapes of contact such as point contact or line contact, the purpose of this research was to develop a haptic sensor. Because the sensor's electrical resistance is stable with elapsed time when very thin MCF rubber film is used, as shown in figure 13, we can conclude that this purpose has nearly been achieved. In other words, a stable haptic sensor has been obtained. Some different contact types of MCF rubber with electrodes will be investigated in the near future.

4. Conclusion

In the present study we have described MCF rubber and how to produce an MCF rubber that can conduct current. We made a trial haptic sensor tip using MCF conductive rubber. We investigated the conductivity of the MCF conductive rubber by experimental methods. To apply the MCF conductive rubber to the production of a haptic sensor, we investigated various relations, for example, the relation of resistance and compressive force, that of resistance and compressive contraction, and the change of resistance with elapsed time. Moreover, we observed the electrical characteristics of the trial haptic sensor tip made from MCF rubber using the same experimental method and schedule.

(i) The larger the compressive force (or contraction) that is applied to MCF conductive rubber, the better the rubber's conductivity will be. In addition, with a compressive contraction over 50 μm (about 15% of the MCF rubber's thickness), the MCF conductive rubber's electrical resistance will drop to the ohm order. This characteristic is very useful when applied to a haptic sensor.

(ii) If the compressive force applied to a haptic sensor made from MCF conductive rubber grows large, then the electrical resistance of the sensor becomes small. When the compressive force is over 15 N, the tip's resistance will be a constant value less than about 2 Ω. At this point, the MCF rubber changes to a good conductor, so it can also be used as a switch.

(iii) In this study, we only investigated the electrical characteristics of the MCF conductive rubber. For use in a haptic sensor, however, it is important to also sense temperature changes. This problem will be studied in the future.

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