Magnetic Actuator Using Double Network Gel

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Soft actuators have been studied actively by many research groups for practical application of artificial muscles. Among them, magnetic soft actuators have been expected to play an active role in the future for a miniaturized actuator. Since it needs no rigid mechanical parts inside and the energy could be transmitted via space, it would be easier to be downsized. Various kinds of magnetic soft actuators, such as rubbers and gel, could be used for this magnetic actuator. In this work, we aimed to improve the strength and the toughness of soft material. We focused on an extremely tough gel material called double network gel, which is composed of a heterogeneous structure of hard gel and soft gel. Double network gel has high strength due to the heterogeneous structure of a hard gel and a soft gel, which has been expected to be used in medical fields such as artificial cartilage due to its high elasticity. We measured the mechanical properties of the gel produced under each production condition and determined appropriate production conditions. Furthermore, the feasibility as a soft actuator was carried out using a thin gel film in which magnetic particles were mixed with a gel and confirming the deformation when a magnetic field was applied.

Keywords: Double network gel, DN-gel, Magnetic particles, Soft actuator

1. Introduction

Recently, many studies on soft actuators have been conducted. For example, the soft actuator using chemical power such as dielectric polymers [1] or ionic liquid [2] or physical power such as a pneumatic actuator [3-8] and magnetic elastomer which was a rubber material dispersed with magnetic particles [9-27] have been developed. Gel and elastomer materials have been used for such actuators. However, these soft materials are weak and fragile so that more strength and toughness have been expected. In this study, we focused on double network gel as one of candidate materials for magnetic soft actuators.

The double network gel has developed by Gong, which is an extremely tough gel material by forming a heterogeneous structure of a hard gel and a soft gel [28-37]. The double network gel maintains its toughness by functioning of a hard gel for compression and a soft gel for tension, and has extremely soft property due to the soft gel at the fracture part. For this fascinating material, Furukawa’s group has developed a forming process, which could be formed into a desired shape like a 3D printer by pulverizing this double network gel and then curing it after dispensing with a syringe [34].

In this paper, we developed a magnetic double network gel that can be actuated by an applied magnetic field. The magnetic double network gel was prepared by mixing magnetic particles with a double network gel using a gel pulverization method used in the above 3D printing system, and we tested the effect on the mechanical properties of the change of the manufacturing method, and the effect on the mechanical properties of the magnetic particles by cutting test. In addition, we carried out an actuation test of magnetic double network gel under an applied magnetic field.

2. Materials

Double network gel has high strength due to the
heterogeneous structure of a hard gel and a soft gel, which has been expected to be used in medical fields such as artificial cartilage due to its high elasticity [35-37]. In these papers, 2-acrylamido-2-methylpropanesulfonic acid (PAMPS) was used as a hard gel, and acrylamide (AAm) was used as a soft gel [28,29]. Aqueous PAMPS solution was prepared at a concentration of 1.0 M, and \(N,N'\)-methylenebis(acrylamide) (MBAA) was added to 4.0×10^{-2} M as a crosslinking agent. 2-Oxoglutaric acid (OA) was also added to 1.0×10^{-2} M as a photoinitiator. AAm (2.0 M) was mixed with only OA (1.0×10^{-2} M). Figure 1 shows the flow of preparing double network material. First, PAMPS solution was cured by UV irradiation. We call this gel the “1st gel”. Subsequently, the cured 1st gel was immersed in AAm and permeated for more than a day. We call the AAm “2nd gel” hereafter. Next, UV light was irradiated again to crosslink PAMPS and AAm and a sample gel was prepared.

We tried to prepared a magnetic field responsive gel by curing double network gel mixed with magnetic particles. However, there was a problem that the magnetic particles could absorb UV and make curing difficult. In addition, it has been also reported that when magnetic particles are coated with alginate ions and mixed into a gel, the strength decreases according to the concentration of the magnetic particles [31]. Then, we prepared a double network gel by soaking the milled 1st gel in PAAm (particles-double network gel) (P-DN gel). Figure 2 shows the flow of preparing double network gel by this method. We pulverized the 1st double network gel with solution of the 2nd gel material. We call this pulverized double network gel as P-DN gel hereafter. We prepared 2 kinds of P-DN gel

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**Fig. 1.** Flow of preparation of magnetic double network gel.

**Fig. 2.** Flow of preparation of magnetic double network gel with pulverization method.
materials without magnetic particles and mixed with 10 mass% of magnetic particles.

As control materials, we prepared a double network gel which was prepared by an ordinary double network gel preparation method, 1st and 2nd network gels (PAMPS gel and PAAm gel, respectively).

3. Cutting test

We performed a cutting test on each double network gel and single network gel. This test was performed with reference to JIS T 8052. In this test standard, the cutter is pressed and then pulled 5 to 50 mm, however, the test piece was pressed until a crack was formed in this experiment without pulling horizontally. The test piece was 40 mm diameter, 50 mm long. A knife edge of 0.5 mm thickness (OLFA Corp.) was used for the cutting test. The speed of the knife edge was set to 1 mm/min. Figure 3 shows an example image during the cutting test.

The obtained load-and-stroke curves are shown in Fig. 4, and the fracture load and stroke of each sample is summarized in Fig. 5. The load of DN gel is about 10 times higher than each single network gel. This is consistent with the results reported in a paper on double network gel [28]. The breaking load of P-DN gel was decreased to 1/8 of that of the original DN gel. This is also consistent with the reference report [29]. P-DN gel consisted of pulverized the 1st gel grains, which were connected by the 2nd gel. This structure was similar as the structure of the fractured surface of the double network gel produced by the ordinary preparation method, and has high flexibility [28]. Both of the load and the stroke of P-DN gel with and without magnetic powder were similar. It is noted that we could prepare magnetic P-DN gel which was mechanically comparable to one without magnetic powder.

4. Actuation test

In this section, we try to actuate the obtained magnetic P-DN gel. We prepared a sheet of magnetic P-DN gel. The thickness was 0.8 mm, and the sheet was cut into 5.0 mm by 10.0 mm. The sample was fixed by acrylic blocks so that the sample was set as a cantilever. The sample was placed between 2 permanent Nd magnets to be applied a magnetic field.

Figure 6 shows the actuated gel under a rotating magnetic field about 60 mT. The gel deformed to be parallel to the direction of the applied magnetic field. The result shows our magnetic DN gel was flexible and could actuate similar as the magnetic silicone actuators [12].

5. Summary

In this paper, we focused on DN gel as a material for magnetic soft actuators. We performed an actuation test of a DN gel sheet mixed with magnetic particles as a feasibility study of a magnetic soft actuator.

There remain some issues. In the future, we will improve a fabrication method to make more homogeneous P-DN gel. In this research, the obtained P-DN gel consists of coarse pulverized grains as shown in Fig. 6. In addition, developing a
3D printing system [10,13-15,18,20,34] for this material is also our future work. The P-DN gel has a feature that it can be formed into an arbitrary shape, but its strength is lower than that of a normal double network gel preparation method. In the future, it will be possible to develop magnetic soft actuators with complex shapes by using P-DN gel with mixed magnetic particles.

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