Development of High-performance ER Gel Produced by Electric-field assisted Molding

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Abstract. Electro-rheological gel (ERG) is a novel functional elastomer whose surface frictional and adhesive property varies according to the intensity of applied electric field. This peculiar phenomenon is named as Electro-adhesive effect. A generated shear stress of ERG under applied electric field is approximately 30~40 times higher than that of ERF because of high adhesive strength. However, the performances of ERG vary widely due to its surface condition, especially density and distribution of ER particles at the surface. In order to stabilize and improve the performance of ERG, the electric-field assisted molding process is proposed as the producing method of ERG. In this study, first, the principle of electro-adhesive effect is theoretically investigated. Second, a high-performance ERG produced by the proposed process, in which ER particles are aligned densely at the surface, is developed and its performance is evaluated experimentally. As the experimental result, the high-performance ERG shows twice higher shear stress than the conventional ERG.

1. Introduction

Electro-rheological gel (ERG) is a novel functional elastomer whose surface frictional and adhesive property varies according to the intensity of applied electric field [1]. This peculiar phenomenon is named as Electro-adhesive effect in order to distinguish from ER effect of ER fluids due to cluster formation of ER particles, which induces change of visco-elastic property under electric field [2, 3]. Figure 1 shows the photo of the actual ERG. ERG is composed of ER particles and silicone gel and has a texture like rubber in appearance. When electric field is applied, ERG provides approximately 30~40 times higher shear stress than that of ERF since high adhesive strength is induced under low electric field such as 0.5kV/mm~1.0kV/mm [4].

However, the performances of ERG strongly depend on its surface condition, especially density and distribution of ER particles at the surface. In order to stabilize and improve the performance of ERG, higher density and precise alignment of ER particles are expected to the production process. In this study, the high-performance ERG is produced by the new method called "the Electric-field assisted Molding Process" and its performance is evaluated experimentally.
2. Estimated principle of Electro-adhesive effect

The ERG sheet was sandwiched between a glass electrode pasted by the conductive ITO film and a metal electrode. A microscope was set above the glass electrode as shown in figure 2(a), and the electro-adhesive phenomenon that occurred on the contact surface between the ERG and glass electrode were carefully monitored. Figure 2(b) shows the electro-adhesive phenomenon of ERG observed in the boundary region under a variable electric field. Upon application of the electric field, the gel adhered to the electrode surface. The higher the applied electric field was, the wider the area of adhesion.

On the basis of electromagnetics, the principle of electro-adhesive effect of ERG is investigated theoretically. In the absence of an electric field, the electrode is in contact with slippery ER particles because ER particle is protruded from the silicone gel. The distribution of electric field at the boundary between ERG and electrode under applied voltage between electrodes is analysed numerically, using ANSYS 11.0 software. Figure 3 represents the electric vector distribution at the boundary area. Four components are microscopically existed at the boundary area: ER particle, electrode, silicone gel and air gap. Electric field in small air gap surrounded between ER particles, silicone gel and electrode becomes high since the permittivity of air is lower than any other material. Moreover, the electric field of air gap increases near the boundary between ER particle and electrode. When the boundary surface between dielectric materials is in parallel and perpendicular with the direction of electric field, the Maxwell stress exerted on its boundary is represented as Eq. (1) and Eq.(2) respectively.

$$F_{n,\parallel} = \left( \varepsilon_2 - \varepsilon_1 \right) E^2 \left[ Pa \right] \quad (1)$$

$$F_{n,\perp} = \frac{1}{2} \left( \varepsilon_2 - \varepsilon_1 \right) D^2 \left[ Pa \right] \quad (2)$$

Where $\varepsilon_1$ and $\varepsilon_2$ are the permittivity of dielectric materials, $E$ is electric field intensity, $D$ is dielectric flux density. As shown in these equations, the resultant total stress due to Maxwell stress acts toward from low permittivity to high permittivity. The interaction of Maxwell stress at each boundary is illustrated in figure 4(a). According to these interactions, ER particles protruding the surface slightly sink down inside though their range of motion is restricted by the elastic deformation of the gel. The soft silicon gel comes up to electrode and, in addition, it is deformed toward the area with higher electric field, i.e. toward the boundary between ER particle and electrode. This is because Maxwell stress increases with increase of electric field intensity. As the result, the sliding electrode makes contact with the sticky gel surface as shown in figure 4(b) and shear force increases. This theoretical estimation based on the Maxwell stress agrees with the observed result and could represent the electro-adhesive effect of ERG [3].

![Figure 2. Electro-adhesive effect of ERG](image-url)
3. Electric-field assisted molding process to produce the high-performance ERG

From the viewpoint of the generation mechanism of ERG effect, it is suggested that the dispersion state of ER particles at the surface significantly influences on the performance of ERG. In order to align ER particles at the surface uniformly and densely, an Electric-field assisted Molding Process is proposed as the new production method of high-performance ERG. The proposed new process is explained in Figure 5. A mixed solution of ER fluid and gelling agent is prepared and poured into a mold. When the metal base and the metal upper plate serve as anode and cathode respectively, the electric field is applied to its solution. By gelling the solution under an electric field, high-performance ERG is produced because the ER particles are arranged densely at the surface along electric lines of force. Figure 6 shows the surfaces of conventional ERG and the high-performance ERG. These ERGs have the same ER particle concentration of 50wt%. As shown in figure 6, it is clarified that the particles at the surface of the high performance ERG are arranged uniformly and densely.

4. Performance evaluation of the high-performance ERG

4.1. Experimental procedure

The basic performance of the high-performance ERG is evaluated by the simple test schematized in figure 7. Two ERG sheets with 0.5 mm thickness are prepared; one is conventional ERG and the other is high-performance ERG gelled under electric field of 1.5kV/mm. A single sheet of ERG is fixed physically on the lower electrode. The upper electrode only put on the ERG sheet and could slide on its surface. Since ERG sheet is sandwiched between a pair of metal plate electrodes, an electric field can be applied to ERG sheet. In this test, the lower and upper electrodes serve as anode and cathode respectively. When an electric field is applied to ERG sheet and the upper electrode slides at the...
constant feed rate, the variation of shear stress between the upper electrode and the ERG sheet is measured using a strain gauge load cell.

**Figure 7.** Schematic diagram of experimental setup for shear test

**Figure 8.** Relation between shear stress and electric field

### 4.2. Basic performance

The relation between the generated shear stress and applied electric field is shown in figure 8. Each deviation of measured shear stress is less than 0.3 kPa. Both conventional and the high-performance ERG exhibit that generated shear stress increases with increase of applied electric field intensity. Compared with two types of ERG, generated shear stress of the high performance ERG is approximately twice as high as that of conventional one. In order to investigate the reason why the high shear stress is generated in high-performance type, the number of ER particles in contact with electrode under electric field is counted by observation of the boundary between ERG and glass electrode. Table 1 shows the comparison of ER particle number per unit area in contact with electrode between conventional and high-performance ERG. The counted particle of high-performance type is twice larger than conventional one. These results indicate that the number of ER particles in contact with electrode corresponds to the generated shear stress. When the ER particles are arranged densely and uniformly at its surface, it is clear that the electro-adhesive effect of ERG can be obtained effectively.

### 5. Conclusion

The high-performance ERG, produced by electric-field assisted molding process, is developed and its basic performance is evaluated experimentally. The high performance ERG shows the higher ERG effect. The generated shear stress is twice as high as conventional one. In future work, the dynamic performance and durability will be evaluated.

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