A Study on Fixing Force Generation Mechanism of ER Gel

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Abstract. Electro-rheological Gel (ERG) is a new functional elastomer which changes its surface frictional and adhesive property according to the intensity of applied electrical field. This unique property is called ERG effect. The upper sliding electrode placed on the surface of ERG is fixed by the adhesive effect of ERG under electrical field. Variable fixing forces due to adhesion are generated by this effect. However, relationship between physical factors and generated fixing force has not yet been clarified. In this study, physical mechanism of fixing phenomenon is elucidated experimentally from the viewpoint of frictional force and adhesive force. From the results, empirical equation of generated fixing force is originally derived to establish the theory of ERG effect.

1. Introduction
Electro-rheological Fluids (ERFs) are functional fluids which change their own viscoelastic properties swiftly and reversibly according to the applied electrical field intensity [1]. This property is called the ER effect. Various devices and equipments have been developed as dampers, clutches using ERFs in a mechanical system [2]. The dispersion type ERFs are composed of ER particles and silicon oil. However, there are two defects of particle type ERFs. Firstly, separation and sedimentation of ER particles over long time reduces ER effect and stability in mechanical system using ERFs. Secondly, necessity of a mechanical seal to prevent leaking ERFs makes system complicated.

The Electro-rheological Gel (ERG) has been developed to conquer these defects of ERFs. ERG is a functional material, which changes its surface frictional and adhesive property according to the intensity of applied electrical field [3]. In this study, this unique property is named as the ERG effect to distinguish from ER effect. The estimated mechanism of ERG effect is shown in figure 1 [4]. ERG is composed of ER particles and silicone gel. ER particles polarize when electrical field is applied. The polarized ER particles attract each other and ER particles existing at the surface of ERG sink into the gel. Therefore, upper sliding electrode placed on the ERG sheet, which is pasted on the lower fixed electrode as shown in figure 2, stick to the gel under electrical field. By the adhesion between surfaces of ERG sheet and electrode, fixing force is generated when the upper electrode is forced to slide. Figure 3 shows the appearance of adhesion between the upper glass electrode and the surface of ERG sheet under various electrical fields. From this phenomenon, it is almost elucidated that the fixing force due to ERG effect is caused by adhesion of gel. However, the physical factors which are contributed to generation of fixing force have not been analyzed enough. In addition, fixing force in normal direction has not yet been evaluated.
In this study, the physical factors of sliding fixing force are experimentally analyzed from the viewpoint of frictional and adhesive property. Based on the results of the analysis, empirical equation of generated fixing force is derived.

2. Experimental apparatus
The influence of the contact pressure and contact area between ERG sheet and upper electrode is investigated to clarify the effect of frictional force and adhesive force respectively.

The schematics of the experimental setup are shown in figure 4. ERG sheet L70×W50×T0.5mm (figure 2) is prepared. ERG sheet is sandwiched between lower fixed electrode and sliding upper electrode. The lower and upper electrode is served as the cathode and anode respectively. Figure 4 (a) shows, an upper electrode is slide aside in sliding direction by a micro screw with motor-drive equipment under various electrical fields. In contrast, a thin metal plate is lifted up in normal direction by z-axis stage via load cell as shown in figure 4 (b). Generated fixing force in both sliding and normal direction is measured by a strain gauge load cell attached to the apparatus.

3. Results
3.1. Fixing force in sliding direction
To investigate how the contact pressure influences on the ERG effect, sliding fixing forces are measured applying the various contact pressures (100, 400, 700Pa) to the center of a sliding upper electrode. The relation between the contact pressure and sliding fixing force is shown in figure 5. Sliding fixing force increases in proportion to the applied electrical field. The initial sliding fixing force increases due to increase of the applied contact pressure. However, the incremental ratio of sliding fixing force is almost constant regardless of contact pressure. Therefore, the generated sliding fixing force owing to ERG effect hardly depends on the contact pressure.

The influence of contact area between ERG and an upper electrode on the sliding fixing force under constant contact pressure is also investigated. The three samples of ERG, which have different surface area of 875mm² (L35×W25mm), 1750mm² (L70×W25mm) and 3500mm² (L70×W50mm), are prepared. As shown in figure 6, generated sliding fixing force increases according to increment of not
The ERG effect is attributed strongly to the change of adhesive property of ERG surface. Therefore, it is possible that surface roughness of sliding electrode became potentially influential factor on ERG effect since adhesive strength depends on the contact condition between the ERG sheet and a sliding upper electrode. The correlation between surface roughness and fixing force is investigated. For this experiment, the three samples of sliding upper electrode, which have different surface roughness Ra of 200nm, 130nm, and 50nm, called as Standard, Fine and Very Fine respectively in this paper, are prepared. The relation between the surface roughness and fixing force in sliding direction is shown in figure 9. Generated fixing force increases with improvement of the surface roughness of sliding electrode in air gap.

3.2. Fixing force in normal direction
It is expected that the ERG generates various fixing force in normal direction since the ERG effect depends on adhesive effect between the surface of ERG and a sliding upper electrode. When the upper electrode is lifted up, the normal fixing force of ERG is measured under various electrical fields. Behaviors of generated normal fixing force are shown in figure 7. Higher fixing force was obtained under higher voltage. Up to the maximum point, the normal fixing force changed linearly with displacement since the upper electrode, which stuck to the ERG through adhesion, is subjected to an elastic force induced by the deformation of ERG. Beyond the maximum point, normal fixing force decreases gradually. This phenomenon is caused by removing on of the upper electrode from the ERG sheet. Fixing force still exists after the upper electrode separates fully from the ERG sheet. This result indicates the existence of the electrostatic force between the upper electrode and the ERG surface. To investigate the distribution of electrical field between the upper electrode and ERG surface, the numerical analysis of electrical field is carried out using the software of ‘ANSYS 11.0’. Figure 8 represents the distribution of electrical field between electrodes with tiny air gap. Electrical field intensity of air gap is achieved to 15.0kV/mm theoretically while electrical field intensity of ERG is 2.0kV/mm. This analysis is conducted under the condition that dielectric breakdown does not occur. From this result, tiny air gap makes the electrical field of the air gap increase remarkably when the upper electrode apart from ERG sheet completely. Consequently, this soaring electrical field generates electrostatic force.

3.3. Influence of surface roughness of the upper sliding electrode
The ERG effect is attributed strongly to the change of adhesive property of ERG surface. Therefore, it is possible that surface roughness of sliding electrode became potentially influential factor on ERG effect since adhesive strength depends on the contact condition between the ERG sheet and a sliding upper electrode. The correlation between surface roughness and fixing force is investigated. For this experiment, the three samples of sliding upper electrode, which have different surface roughness Ra of 200nm, 130nm, and 50nm, called as Standard, Fine and Very Fine respectively in this paper, are prepared. The relation between the surface roughness and fixing force in sliding direction is shown in figure 9. Generated fixing force increases with improvement of the surface roughness of sliding electrode in air gap.
both directions. This result indicated that higher adhesive force due to ERG effect is obtained by making the surface of sliding electrode finer.

3.4. Theoretical model derived from the experiment analysis

In the past study, it is confirmed that gel contact area is proportional to electrical field intensity [4]. From this relation and the experimental result in this study, the empirical equation of maximum sliding fixing force $F_s$ [N] and maximum normal fixing force $F_n$ [N] just before sliding and detaching between ERG and upper electrode is derived as follow.

$$ F_s = \mu_0 N + C \alpha SE \quad (1) $$

$$ F_n = \frac{1}{2} \varepsilon SE^2 + C \alpha SE \quad (2) $$

where $\mu_0$ is the frictional coefficient of ERG, $N$ [N] is the normal force for applying to ERG surface, $C$ [N/mm$^2$] is the adhesive force of gel per unit area, $\alpha$ is the increasing rate of gel contact area per unit electrical field, $S$ [mm$^2$] is the contact area between the ERG surface and upper electrode, $E$ [kV/mm] is the applied electrical field of ERG, $\varepsilon$ [F/m] is the permittivity of ERG, $\alpha$ also depends on surface roughness of the upper electrode, whose magnitude is in order of $10^{-3}$~$10^{-4}$. Maximum sliding fixing force $F_s$ is represented as resultant force of initial friction force $\mu_0 N$ and adhesion generated by ERG effect. On the contrary, maximum normal fixing force $F_n$ is as resultant force of electro static force $\varepsilon SE^2/2$ and generated adhesion.

4. Conclusion

In this study, relation between generated fixing force according to the ERG effect and physical factors is experimentally analyzed from the view point of frictional force and adhesive force. It clears that generated fixing force depends greatly on adhesive force due to ERG effect, although frictional force and electrostatic force make little impact on it. Based on the experimental results, the empirical equation of generated fixing force is obtained in both sliding and normal direction. In addition, impact on fixing force according to the surface roughness of a sliding upper electrode is also investigated. Finer surface roughness of a sliding upper electrode gives well fixing force.

References

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