Observation of charge separation and gas discharge during sliding friction between metals and insulators

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Abstract. Charge generation due to friction between stainless steel and fused quartz in a vacuum was measured, and it was found that the density of the charge separation at the friction contact was $4 \times 10^{-4}$ C/m$^2$. In experiments in ambient gas, reduction of the separated charge caused by microgap gas discharge was observed. The residual rate of the charge, which is the ratio of charge accumulation in an ambient gas to that in a vacuum, in argon ambient gas was small, and it seemed to be effective for the relaxation of generated static electricity due to friction between solids.

1. Introduction
Gas discharge is one of the well-known origins of triboluminescence. Previous microscopic studies of triboluminescence make it clear that the gas discharge occurs in a microscale gap between electrified surfaces around the real contact during friction between solid materials [1]. In other words, the gas discharge acts to reduce static electricity due to charge separation in friction.

To prevent accidents caused by static electricity, such as explosion and fire at an industrial chemical plant, suppression of the charge accumulation is essential. A part of the negative and positive charges separated due to friction is recombined as a result of the microgap gas discharge around contact. We need to investigate the mechanism from the charge generation to the gas discharge in detail.

In the present study, the charge accumulation during friction was measured in a vacuum and in several ambient gases and at several pressures. The efficiency of the charge reduction due to the gas discharge was evaluated by the residual rate of charge derived from the measurements.

2. Experimental setup
Figure 1 shows the experimental equipment of the present study. One purpose of this study is to measure the static electricity generated by sliding friction between metals and insulators under controlled ambient gas conditions. The mechanics of sliding friction between solids was based on a pin-on-disk technique. This type of equipment was also used in previous studies of triboluminescence [1].

The pin and the disk were settled in a vacuum chamber in order to control the ambient gas, such as the kind of gas, pressure, and humidity of the air. The gas was pumped out by using a turbomolecular pump combined with a scroll pump as a fore-vacuum pump; the pumping system was completely...
operative without oil pollution, and the samples in the vacuum chamber were kept clean. The pressure was measured with a diaphragm gauge and an ion gauge: typically, the base pressure of the vacuum is $1 \times 10^{-3}$ Pa, and this state is defined as a vacuum condition in this study.

The chamber is made of stainless steel and grounded electrically, so the friction is performed inside the space shielded electromagnetically: this gives higher reliability to measurement of the static electricity by means of an electrometer.

A pin made of stainless steel was used in this study. The tip of the pin was a spherical surface with a radius of 0.5 mm. The pin was held at the end of an arm with a pair of plate springs fixed on a 3-axis manipulator, as shown in Figure 1. The contact force of the friction could be adjusted by the manipulator from outside the chamber without breaking the vacuum and gas condition. A strain gauge fixed on a plate-spring surface is sensitive to deformation, and then normal force at the contact is detected. It was fixed to 130 mN in the experiments.

The disk was made of synthetic fused quartz, which is optically transparent; its diameter was 50 mm, and its thickness was 1 mm. The contact area between the tip of the pin and the disk surface was directly observed with a microscope and a CCD camera from outside the chamber through the disk and a viewport as shown in Figure 1. The diameter of the circular contact, which corresponds to the width of the friction track, $w$, was 40 $\mu$m.

The rotational speed of the disk, $n$, is controlled with a micro-step stepping motor at a fixed speed. The sliding velocity of friction, $v$, can be calculated from $n$ and the distance between the contact and the centre of the disk rotation, $r$; in the present experiments, $v = 0.75$ mm/s ($n = 0.005$ revolution per second (rps) and $r = 24$ mm).

The metal pin was directly connected to the electrometer input; the electrical charge generated on the metal side could be measured, and the charge accumulation was monitored during the sliding friction in real time.

![Figure 1. Experimental setup](image)

![Figure 2. Charge accumulation during friction in a vacuum and ambient gases at different pressures](image)
3. Results
Figure 2 shows the experimental results: the charge accumulation during the sliding friction between stainless steel and fused quartz in a vacuum and four kinds of ambient gases was measured. The results in a vacuum are shown in Figure 2(a) and 2(b). As a result of the present experiments, it was found that the stainless steel was electrified positively and the fused quartz was simultaneously negative. The charge accumulation developed at a fixed rate under the constant velocity of friction. In the process of charge accumulation in a vacuum, charge recombination caused by gas discharge did not occur; therefore, the fixed rate of the charge accumulation, \( dq/dt \), indicates initial charge separation due to friction, i.e., essential triboelectrification without charge back-flow. The charge density of the initial charge separation at the contact, \( \sigma \), could be estimated using an equation, \( \sigma = (dq/dt)/vw \); the result of calculation is \( 4 \times 10^{-4} \) C/m².

Experimental results for nitrogen gas at pressure of 1 and 0.4 atm are shown in Figure 2(a). It was confirmed that friction between solids in an ambient gas was accompanied by gas discharges [1]. The discharges were clearly observed as intermittently sudden reductions of the charge accumulation. At 0.4 atm of nitrogen gas, the amount of discharge was almost equal to all of the accumulated charge; this was always repeated during sliding friction. Therefore, the charge accumulation remained at a low value, while the rate of the charge separation, i.e., the slope of the accumulation process, was almost the same as that in a vacuum. In the case of measurement at 1 atm of nitrogen gas, the nature of the charge accumulation and the discharge process was almost the same as that of the measurement at 0.4 atm. The charge reduction was, however, small in comparison with the accumulated charge after the last discharge. Therefore, the charge cancelation was insufficient to erase the electrification on the fused quartz surface totally.

Figure 2(b) and 2(c) show measurements of argon gas and dry air, respectively. Results in the case of the dry air were similar to the case of the nitrogen gas, as shown in Figure 2(a). The value of the charge accumulation remained low at 0.4 atm due to the gas discharge; however, the cancelation was insufficient, and the “residual charge” accumulated slightly in the 1 atm pressure. In the case of the argon gas, the gas discharge was sufficient to erase the charge accumulation at both 1 atm and 0.4 atm.

Introducing room air to the vacuum chamber, the charge accumulation during sliding friction in atmospherically humid air was measured, and the results are shown in Figure 2(d). The temperature was 27 degrees centigrade, and the relative humidity was 66%. It was found that development of the charge accumulation at 0.4 and 1 atm was very smooth and lower than that in a vacuum. There is, however, no sudden falling of the charge accumulation.

![Figure 3. Residual rate of charge under the gas pressure of 1 atm](image-url)
Table 1. Experimental results of residual rate and reference data of the corona starting gradient [2]

|                  | Residual rate (%) | corona starting gradient (kV/cm) |
|------------------|-------------------|---------------------------------|
|                  | 1 atm             | 0.4 atm                         |
| N₂               | 32 ± 7.4          | 0.9 ± 1.3                       |
| Ar               | 0.5 ± 0.2         | 1.8 ± 0.5                       |
| Dry air          | 40 ± 6.0          | 4.4 ± 0.9                       |
| Atmosphere       | 28 ± 1.3          | 22 ± 1.6                        |

4. Analysis and discussion

Figure 3 shows the residual rate of charge. These curves are produced from the ratio between the measurement of the charge accumulation in an ambient gas at 1 atm and the measurement in a vacuum at each time. For example, the residual rate in the case of friction under dry air is about 40% in the range between 50 and 150 seconds. This means that electrification of the fused quartz surface due to friction with a stainless steel pin under dry air was only 40% of the initial charge separation; in other words, 60% of the charge generated by friction is eliminated by gas discharge in a microgap. Remarkably, the residual rate of charge is very small in the case of the argon ambient gas.

The average and standard deviations of the residual rate of charge in the range between 50 and 150 seconds were calculated from the data. The results are shown in Table 1. The electric field needed to ignite the corona discharge in each gas at 1 atm [2] is also indicated in the table for reference. In nitrogen, argon, and dry air at 0.4 atm, the microgap discharge could effectively reduce the electrification on the fused quartz surface. However, nitrogen and dry air at 1 atm were not affected sufficiently to eliminate the charge by discharge. Argon gas worked strongly to eliminate electrification, even at 1 atm.

The residual rate of charge in the atmosphere at 1 atm was 28%. Although this is smaller than that in dry air (40%), microgap discharge, i.e., a sudden reduction of charge, was not observed. The effect of humidity on this charge relaxation has not been revealed.

The charge density before the microgap discharge was calculated to be 4x10⁻⁴ C/m² from the charge measurement in a vacuum; the electric field in a microgap should be 450 kV/cm. While it is much higher in comparison with the electric field for ignition of the corona discharge, the fact that the ignition field of argon is small seems to indicate that the residual rate was very low in the experiment in the case of argon gas.

5. Summary

Charge generation due to friction between stainless steel and fused quartz in a vacuum was measured, and it was found that the density of the charge separation at the friction contact was 4x10⁻⁴ C/m². In experiments in ambient gas, reduction of the separated charge caused by microgap gas discharge was observed. The residual rate of the charge in argon ambient gas was smallest, and it seems to be effective for relaxing the static electricity generated due to friction of solids.

Acknowledgments

This work was supported by JSPS KAKENHI Grant number 25350491, Grant-in-Aid for Scientific Research (C).

References

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