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Contact charge accumulation and separation discharge

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ABSTRACT

The cumulative triboelectrification of solids by repeated contact and separation is not completely understood. For nominally identical contact, the transferred charge often requires multiple cycles to saturate, and in some cases does not saturate at all. Several explanations have been proposed for this behaviour, but quantitative validation is complicated by the potentially dominant role of separation discharge. This paper presents a new method for controlling or suppressing the discharge, without affecting the initial transferred charge. The phenomenon of separation discharge is described, and its effect on charge accumulation speculated upon. The proposed charge measurement technique is then discussed quantitatively. Lastly, the design and construction of a prototype experimental apparatus are described.

1. Introduction

It is often remarked that contact charging, one of the earliest observed electrical phenomena, is one of the most poorly understood. When two dissimilar materials are brought into contact and separated, one will become positively and one negatively charged; however, the magnitude of this charge is often very difficult to predict. This is in part because the measured contact charge tends to be determined by a mixture of factors that are difficult to separate experimentally [1,2]. Contact charge accumulation is no exception. Consider two insulating surfaces in contact. Even if the charge transfer of charge between the surfaces has come to equilibrium during this contact, subsequent nominally identical contacts after separation usually result in a further transfer of charge. The reasons for this are usually multiple, and vary from system to system.

Electrostatic discharge between contact-charged bodies is often observed as they are separated, and is associated with breakdown of the intervening gas. This phenomenon occurs when the charged bodies are relatively widely separated, and is quite distinct from other charge transfer mechanisms. The significance of separation discharge in many systems has long been recognized [3], and lies in the fact that it reduces the magnitude of the separated charge. Its important role in determining the final charge of particles after impact has been comprehensively demonstrated [4]. While individual discharges have been identified and measured during the separation of contact-charged bodies [5,6] the effect on subsequent contact charging and charge accumulation is unknown. In particular, the effect of charge accumulation mechanisms operating in conjunction with separation discharge is not understood. Since it is usually difficult to measure the contact charge until the contacting bodies are separated, the separation discharge can complicate study of charge transfer mechanisms during contact. It can also cause confusion in practical contexts where it is necessary to predict the final tribo-charge. For instance, materials are often ranked in a 'triboelectric series' as a guide to their triboelectric chargeability for the purposes of triboelectric separation, toner charging, pharmaceutical particle handling, and so on (e.g., [7]). Their position in the series is often identified strongly with the surface work function, without reference to discharge. Better understanding of discharge characteristics may allow more judicious application of particle processing techniques that involve triboelectrification. For these reasons, it is highly desirable to perform identical charge accumulation experiments, with and without separation discharge, to achieve two main objectives: (i) to study other charge transfer processes without the complicating role of discharge; (ii) to study the effect of discharge itself upon charge accumulation. In many previous repeated-contact studies [8,9] discharge has been suppressed by performing the experiments in vacuum. Unfortunately, this both avoids the issue of investigating the charging of 'real' systems in air, and yields no information on the effect of the discharge. Medley [10] devised

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a method for suppressing the discharge in air, and indeed used this method to demonstrate the effect of the discharge upon the final contact charge. In Medley's experiment, one contacting body was an extremely thin polymer film backed by an earthed reservoir of mercury. From the vantage point of the other contacting body, the effect of the image charge on the front surface of the mercury was to reduce the difference in potential between the contacting surfaces when separated. For this to have a substantial effect, the thickness of the polymer film had to be of the order of the first-discharge separation (typically $\sim 1\,\mu m$) or smaller, and the discharge could only be suppressed slightly. The experiment was also limited in the materials that could be explored, and with its mercury reservoirs, was very inflexible and unwieldy. In this paper, we propose a method for controlling or suppressing the separation discharge without affecting the contact charge transfer. This method involves application of an external bias that cancels or reduces the electric field between the charged bodies that leads to breakdown of the intervening gas. In conjunction with a sophisticated system for measuring the surface charge or interfacial force (e.g., the technique of Smith [11]), discharge control may yield very detailed information about the effect of separation discharge. A prototype apparatus is described; it is hoped that this will provide an initial 'proof of concept' for the technique.

2. Discharge and accumulation

We now briefly discuss the separation discharge and speculate qualitatively as to its interaction with other accumulation and backflow mechanisms. Fig. 1 shows the essential features of the discharge process graphically, as proposed by Matsuyama and Yamamoto [12]. As the charged bodies recede from one another, the potential difference between them increases (for example, for

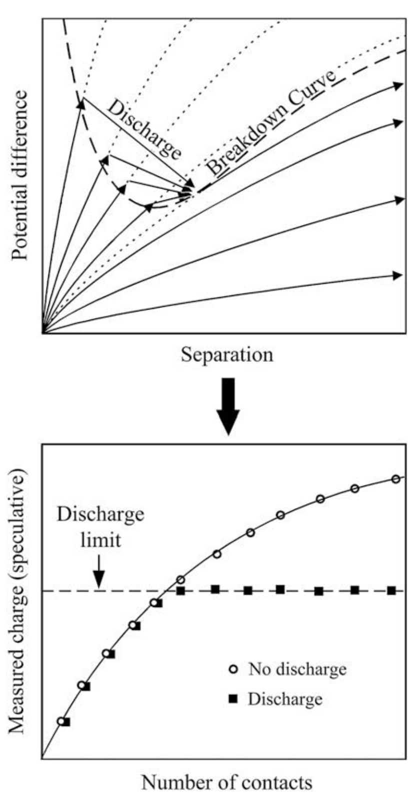

Fig. 1. Separation discharge scheme proposed by Matsuyama and Yamamoto [12], for a single breakdown/extinction curve. Discharge occurs during every separation.

infinite surfaces with equal and opposite charge density of magnitude $|\sigma|$ and separation d, the potential difference goes as $|\sigma|\,d/\varepsilon$). At some separation, the potential difference attains the breakdown value (as determined by the Paschen law curve or equivalent) of the ambient gas, whereupon discharge occurs and a portion of the contact charge returns whence it came. Horn et al. [5] were able to record these discharges, and their data seem inconsistent with a single breakdown curve, even for a series of partial discharges; the possibility of separate breakdown and extinction conditions must therefore be included in any consideration of separation discharge [13].

At a simple level, contact charge exchange is often described using the analogy of capacitor charging:

$$\sigma = \sigma_0\left(1 - e^{-t/\tau}\right), \tag{1}$$

where σ is the transferred charge per unit area of the interface, σ_0 is a saturation charge density which nullifies the driving potential difference, and τ is a characteristic time over which the process occurs. If the time available for charging is much greater than τ, the transferred charge will saturate. Several mechanisms have been identified that allow charge transfer beyond the single-contact saturation density multiplied by the nominal contact area. These include conduction, contact non-redundancy and contact deformation. Conduction is an obvious factor in repeated-contact charging of isolated metals; once contact is broken, the charge is spread over the entire surface of the metal object, and the density in the contact region is depleted accordingly. However, even nominal insulators may be sufficiently conductive that a substantial amount of charge is dispersed from the immediate contact area between contacts [14,8]. The expected effect of conduction is therefore to increase the incremental charge transfer during subsequent contacts, and this effect will presumably increase as the time between contacts increases. However, during contact with a conductor, this dispersed charge may be attracted back to the contact area by its image on the conductor, and may even flow back into the conductor. This mechanism will therefore produce a decreased charge transfer with increased duration of contact. The saturation charge is also determined by the contact area. If the region of contact is not identical for all contacts, additional charge can be transferred to the 'virgin' part of the surface [15,16]. At a microscopic level, surfaces often make contact over a surprisingly small proportion of the apparent interfacial area [17], and the non-redundant area between two contacts may be much larger than suggested by any macroscopic misalignment. Furthermore, plastic deformation of the interface due to the contact pressure may progressively increase the surface area [8,18] leading to a saturation charge that increases with total contact time.

The effect of the separation discharge will presumably depend on the type of accumulation mechanisms present, and the form of the breakdown and extinction limits for the discharge. Consider charge accumulation in combination with the separation discharge scheme of Matsuyama and Yamamoto [12], as shown in Fig. 1. If a pair of contact-charged bodies recede with less than a particular critical charge density, the full transferred charge will still be present at large separations. If the critical density is exceeded, discharge reduces it to a constant discharge-limited value, as shown. However, if there are separate breakdown and extinction curves (Fig. 2), as suggested by the data of Horn et al. [5], the charge may fall well below the critical density for discharge, and take a number of further contacts to accumulate to the critical density, resulting in repeated discharge and accumulation cycles as the charged bodies recede. It is also possible that the real mechanism is more complicated than either of these model schemes.