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A Novel Non-Contact Macroscopic Triboelectric and Tribological Measurement Device

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Abstract— **A combined tribological and triboelectric characterization tool has been developed to study the dynamics of contact electrification between sliding surfaces. Triboelectricity is generated by sliding contact between a stationary rod and a moving polymer band. The tool can measure the static and dynamic force of friction and the resulting charge density on the surface *in situ*. The force of friction is measured with a load cell that pulls on the band by motion of a stage at <1 mm/s, and the charge density on the surface is measured at two points by deflection of independently shielded metallic cantilevers. The deflection was calibrated to absolute charge density using an electrometer. The force of friction was found to respond to static charges on the band after sliding in a high vacuum environment with an increase in the friction force in vacuum compared to sliding at atmospheric pressure. Friction and charge were also correlated during abrupt changes in the charge density that represent dielectric breakdown events. We observed non-uniform spatial charge distributions such as patterning in the form of repeating peaks and discontinuities. Simultaneous measurement of these key variables *in situ* generates an integrated picture of triboelectric, tribological, and discharge phenomena with macroscale spatial resolution and microsecond temporal resolution.**

I. INTRODUCTION

Much work has been done in the areas of triboelectric and tribological properties of materials, including the relationship between applied normal force and charge density [1]. However, little has been done to understand how the frictional force governs the triboelectrification, and the converse, how electrified surfaces can affect the frictional force. The study of triboelectricity has become even more valuable recently with the observation of direct X-ray generation from the triboelectric effect. Researchers from UCLA have shown low intensity mechanical work applied between two surfaces can generate sufficient flux and energy to expose an X-ray radiograph [2]. A better understanding of the surface-surface interaction is critical to understanding this phenomenon.

Charge measurements on microscopic scales are commonly made with Electronic_with Electronic Force Microscopy (EFM), Kelvin Probe Microscopy, an electrostatic voltmeter, and an electrometer with a Faraday cup probe. There are a few examples of people who have made charge measuring devices capable of measuring the instantaneous spatial distribution of charge. Bearsdmore-Rust et. al. [3] have made a charge camera by constructing an array of electrostatic voltmeters as pixels, using a known charge to calibrate the system. Similarly, Faircloth and Allen [4] used an electrostatic voltmeter attached to the end of a moving probe. The EFM method has a modified Atomic Force Microscope (AFM) tip that can measure local microscale electric fields with no inherent drift, allowing for measurements on timescales of >1 hour. Other techniques mentioned are plagued by drift due to parasitic capacitances in the system and by crosstalk.

Using Kelvin Probe Microscopy, Burgo et. al. [5, 6] observed that with both positive and negative charge on the surface of a dielectric after contact, despite the net negative surface charge. This suggests that charge transfer mechanisms and the resulting charge distributions can be complex. Collins et. al. [7] have demonstrated that this patterning can be seen on the macroscopic level as well. A device that can generate charge transfer from the triboelectric effect and simultaneously measure the magnitude and distribution of the charge transfer *in situ* with good spatial resolution might be useful for furthering the understanding of such mechanisms.

In this paper, we describe a triboelectric and tribological measurement device that can measure the nature of charge transfer between two materials with good spatial resolution, measure the frictional force added by that charge transfer, and observe aspects of electron discharge as well. Selection of a cantilever probe eliminates electronic drift in the measurement and permits observations over long time scales. A degree of spatial resolution and locality is achieved by adding an array of multiple independently shielded cantilevers. By calibrating each cantilever with a known surface charge we can see complete charge maps of the polymer surface resulting from contact with a metal rod. The temporal resolution is only limited by the natural resonance of the cantilever, which is roughly 20Hz. This permits sub second resolution of the triboelectric effect and allows for tuning of the cantilevers for higher temporal resolution.

II. DEVICE

The device is a custom triboelectric and tribological measurement tool that can measure static and dynamic friction between a mobile polymer band and a stationary rod, the resulting triboelectric charge density, Young's Modulus of the polymer band, and the rates of discharge phenomena. A diagram of the device is shown in Fig. 1. Triboelectrification of the polymer band occurs as it slides over a 90° wrap angle over the rod. The polymer band is clamped to a hanging weight that applies downwards tension on one end, and is clamped to a 10kg load cell and linear stage at the other end. The band is pulled by the stage at a speed of 5 – 5000μm/s, and a linear range of 20mm. The device has two independent cantilevers that can measure the charge on the moving surface of the polymer band. The two side-by-side cantilevers can be aligned along the length of the band (as shown in Fig. 1), or along its width.

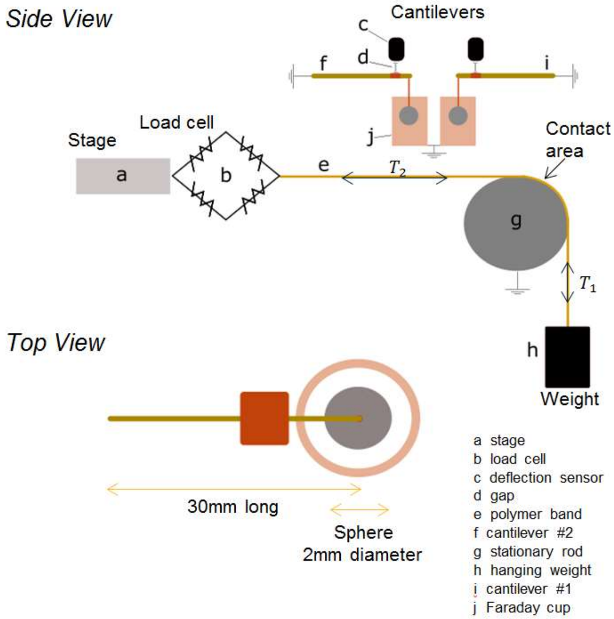

Fig. 1. An illustration of the device (not to scale). The side view shows the important components with a key in the lower right. Cantilever #1 is located closest to the rod, and Cantilever #2 is located downstream from #1. The top view shows the dimensions of the cantilever, and highlights the square Copper inductor reference plate used to amplify the signal between it and the inductive displacement sensor.

The cantilevers shown in Fig. 1, are made of five parts: a bar, a sphere, a wire and a plate that are soldered together. The sphere is attached to the end of the bar via the wire, and the reference plate is 1mm from the end of the bar. The spheres are suspended within a grounded cylindrical Faraday cup that is held independently and does not touch the cantilevers. The spheres are located above the sliding contact 3mm from the band surface. The first cantilever is positioned such that the center of its sphere is 5mm from the peeling vertex, and the 2nd sphere is located 6mm downstream from the first sphere. The cantilevers are grounded at their fulcrums where they are clamped, and everything, except the polymer band, is grounded together at one location. The deflection of the cantilever due to charges on the band, on the order of 1mm, is measured with a linear displacement inductor sensor that can measure displacements of >1µm. The displacement (δ) of the cantilever can be related to force (F) on the bar, Young's Modulus (Y), and the dimensions of the bar (t,w,l) by Eqn.1 that holds for t<<w and l:

$$\delta = \frac{4}{Yw}\left(\frac{l}{t}\right)^3 F \tag{1}$$

The grounded sphere on the cantilever experiences a force ($\vec{F}$) due to the charge on the polymer band that can be calculated by the integral of the Maxwell stress tensor over the surface of the sphere:

$$\vec{F} = \oint_S \overleftrightarrow{T} \cdot \overrightarrow{dS} \tag{2}$$

The Maxwell Stress Tensor is written:

$$T_{i,j} = \varepsilon_o E_i E_j + \frac{1}{\mu_o} B_i B_j - \frac{1}{2}(\varepsilon_o E^2 + \frac{1}{\mu_o} B^2)\delta_{i,j} \qquad (3)$$

Neglecting contributions from magnetic fields, the force on the sphere is proportional to the square of the electric field generated by charges on the polymer, $|\vec{F}| \propto E^2$. It follows that the force and tip displacement of the cantilever sphere are proportional to the square of the charge density (σ) on the polymer surface, $\delta \propto |\vec{F}| \propto \sigma^2$. The Faraday cup that surrounds each cantilever sphere narrows the area of sensitivity to charges near the entrance of the cups by screening. We estimate the area of sensitivity at the location of the band is ~$1cm^2$.

It is impossible to solve an analytic, closed form solution of Eqn. 2 for a grounded sphere suspended over a charged dielectric. Accordingly in order to measure absolute charge density it is necessary to calibrate the cantilever to a known charge. The deflection of each cantilever was calibrated to absolute charge density with a known charged area established with an electrometer and Faraday cup probe. Calibration functions were generated by placing a known charged area under the cantilevers. Charged areas of different dimensions were measured to quantify the field of view of each cantilever.

The device can be used at any pressure between ambient and <1e-5mbar, but in order to measure the triboelectric effect the device operates in vacuum because the presence of moisture and gas can both confuse the measurement and can provide a short circuit path to ground. Experiments are performed in vacuum <1e-4mbar.

III. MEASUREMENTS

Static and dynamic friction can be measured by time evolution of band tension during slow sliding motion of the band over the rod. Figure 2 illustrates two distinct friction regimes. From rest, tension is applied to the band by the linear stage until the tension in the horizontal part of the band (T_2) equals the force of friction (F_f) plus the force of the hanging weight $(T_1 = m_{weigh}\ g)$. At this point the band/rod interface slips and static friction is measured by a peak in F_f. The frictional force is calculated by Eqn. 4.

$$F_f = T_2 - T_1 = T_{load\ cell} - m_{weight} g \qquad (4)$$

While in motion, the dynamic force of friction evolves in a complicated way due to contributions on F_f by triboelectrification and by time dependent loading of the two band segments that hang over the rod. The band continues to slip as the stage pulls at constant speed of 50µm/s until a maximum displacement of 20mm is achieved, at which point the stage retracts -20mm to complete one cycle. Coefficients of friction (μ) can be calculated by the Capstan Equation (Eqn. 5) with $\beta = \frac{\pi}{2}$ for a 90° wrap angle.

$$\frac{T_2}{T_1} = \exp(\beta\mu) \qquad (5)$$

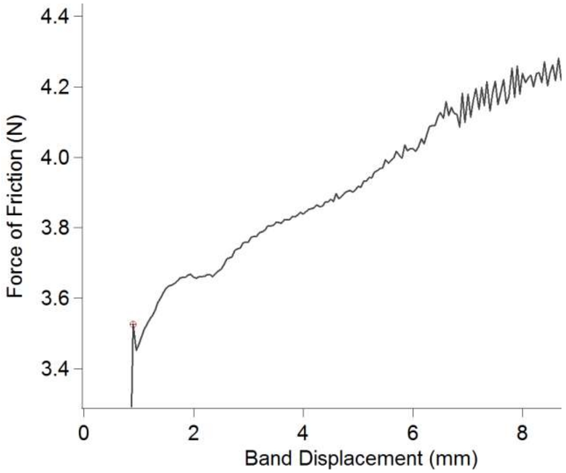

Fig. 2. Force of friction as a function of band displacement at 50μm/s. The first peak from the left represents static friction. The remaining data to the right shows non-uniform time evolution of dynamic friction.

Young's Modulus (Y) can be measured by the initial stretching period where the band has not yet slipped. The change in force (ΔF) divided by the strain ($\frac{\Delta l}{l_i}$) before slip returns Y within 50% of the known value for the band material.

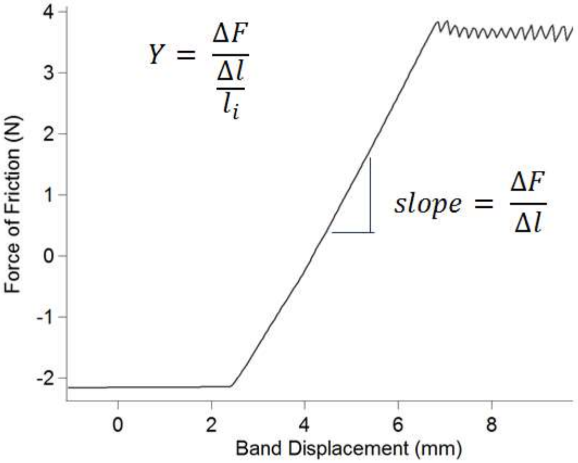

Fig. 3. Initial stretching period of the band before slip. The slope and initial band segment length (l_i) together give Y.

As discussed in Section II, the deflection of the cantilever tip is related to the square of the charge density on the polymer band as $\delta \propto \sigma^2$. Without calibration, the deflection of cantilever tip represents a relative measure of the charge density. Relative charge density can be used to qualitatively compare the charging performance of different pairs of materials, and can measure ~1mm structures in charge density distributions.

To quantitatively measure charge density, the output voltage of the inductive deflection sensor (corresponding to tip deflection) was mapped to absolute charge density by a known charged area measured independently with an electrometer. The resulting absolute charge density of the moving band measured with two cantilevers is shown in Fig. 4. Before any sliding motion has occurred, the cantilevers are zeroed to a pristine uncharged area of band. As the band generates charge density through sliding, it approaches the cantilevers and exerts a force on them in sequence of cantilever #1 and then #2 according to their relative position downstream from the rod. The shielded fields of view cause the cantilevers to respond mostly to charges directly beneath and ± 5mm up and downstream from it. This effectively causes each cantilever to measure a ~$1cm^2$ area on the polymer surface at any instant. Charge densities of between $1x10^9 - 5x10^{11}\ \frac{e^-}{cm^2}$ can be measured and are limited by the sensitivity of the displacement measurement and the charge density domain of the calibration.

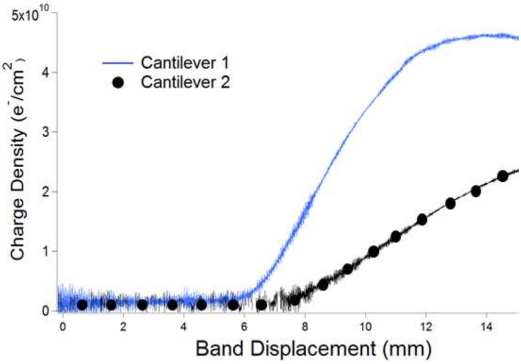

Fig. 4. Absolute charge density of a sliding band as a function of band displacement distance. The charge density represents the calibrated output of the inductive position sensor.

In addition to friction and charge density, the device can measure two distinct discharge phenomena: field effect emission rate and breakdown. Once the charge has been generated through tribocharging and has separated from the contact, the electric field grows with the dimensions of the charged polymer area. Given the right material pairing, the field grows high enough to initiate field emission from the polymer surface to ground. At even higher fields, breakdown either through the polymer or through vacuum can occur. Discharge is the reason why cantilever #2 always returns a lower and more uniform charge density than cantilever #1.

The rate of field emission can be measured directly by relaxation of the cantilevers over a stationary charged area, shown in Fig. 5. After several displacement cycles a charged area is parked beneath cantilever #1 and is allowed to discharge itself over >100min until it asymptotically approaches a zero charge density limit. The curve is roughly exponential with a decay time constant of ~12min. A double exponential fits better with time constants of 4min and 20min, suggesting two different discharge processes. An attempt was made to measure charge mobility in the in-plane direction without success, indicating that the rate of discharge by field emission in the out of plane direction is much greater than any in-plane mobility that may be present. According to these observations, charge decay observed in Fig. 5 is mostly due to field emission. Alternatively, decay constants can also be measured from the instantaneous difference in charge densities measured at each cantilever. The secondary method gives answers consistent with the first method.

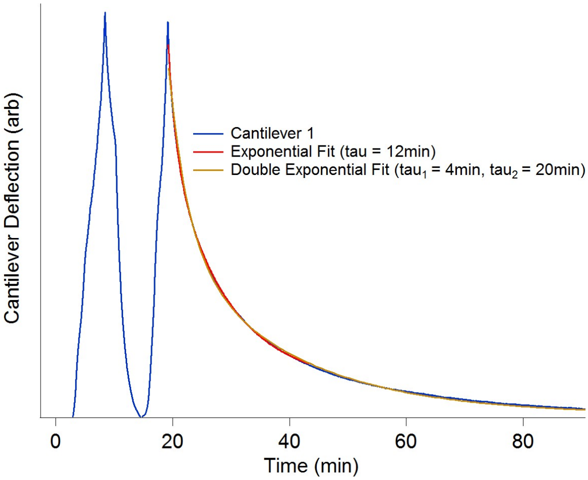

Fig. 5. Long time scale decay of cantilever deflection over a charged area. Decay represents field emission at high fields from the polymer band to ground. The decay curve can be fit with an exponential.

Based on the material pair, electrified area, and gas pressure, breakdown can be observed and is illustrated in Fig. 6. Nanosecond discharges dump >95% of the charge density from cantilevers' field of view during the breakdown process, forcing the deflection and band tension to decrease abruptly. These events show an obvious correlation between increased band tension and charge density. Currently the mechanism is unknown, but during these events the charge may affect friction through the coefficient of friction, through normal force between band and rod during contact, or even long range force between separated charges on the polymer surface and ground. More work will be done to understand the contribution of charge to the frictional force in vacuum.

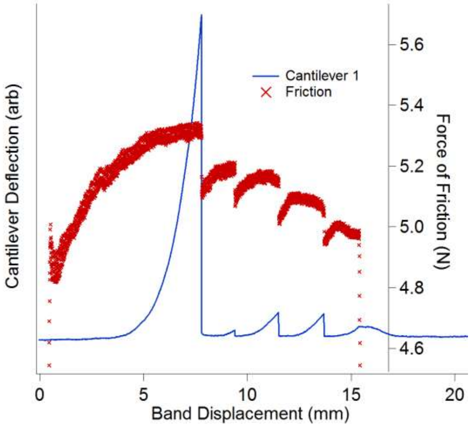

Fig. 6. Friction and deflection show abrupt changes during breakdown events. The field goes to zero and the friction decreases during these events. This example is one of the few times where friction and charge density appear to be correlated.

IV. OBSERVATIONS

Non-uniform charge distributions have been observed on occasion given the right material pairing and experimental conditions. Repeating peaks shown in Fig. 7 are interpreted as macroscopic charge patches. Both cantilevers can see the patches as they move beneath them and even persist several minutes later as the band moves backwards to complete the cycle. Charged patches have been reported in the literature with microscale cantilever force probes [3]. These patches are on the order of >1mm and are spaced at 6mm peak to peak. Simulations were done to verify if indeed charged patches could cause the observed deflection behavior, and if so, what the details of such patches could be. This work is reported by Eli Van Cleve in a separate report in these proceedings.

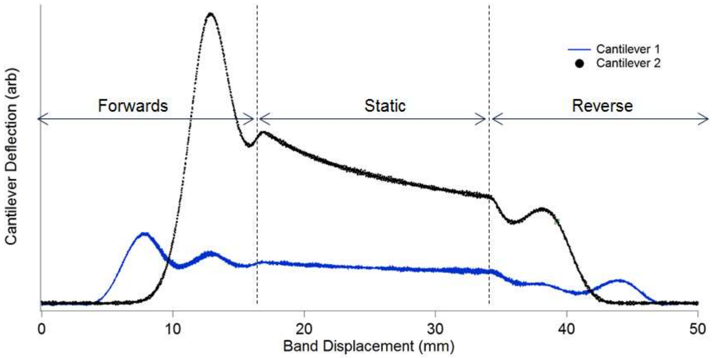

Fig. 7. Evidence of charge patches. Repeating peaks in cantilever deflection can be observed. Experiment was run at 5µm/s.

Stick-slip motions on the order of 0.1mm of the band traveling at slow displacement speeds of ~5μ/s have been observed in both the friction and charge measurements. A zoomed in view of the raw data in Fig. 8 shows sudden drops in the band tension correlated with stepwise increases in cantilever deflection. The sawtooth-like tension profile represents successive loading/releasing of mechanical energy stored in the band, which causes it to slip in increments. The cantilever deflection also supports the same picture as it deflects downwards in a stepwise manner as charge is moved beneath it in increments. Another subtle feature of the cantilever signal is that despite the constant and inevitable field emission that bleeds charge from the band and decreases cantilever deflection, a shallow positive slope is observed while the band stretches during the sticking phase. This is due to the miniscule charge translation in the plane of the band while it stretches.

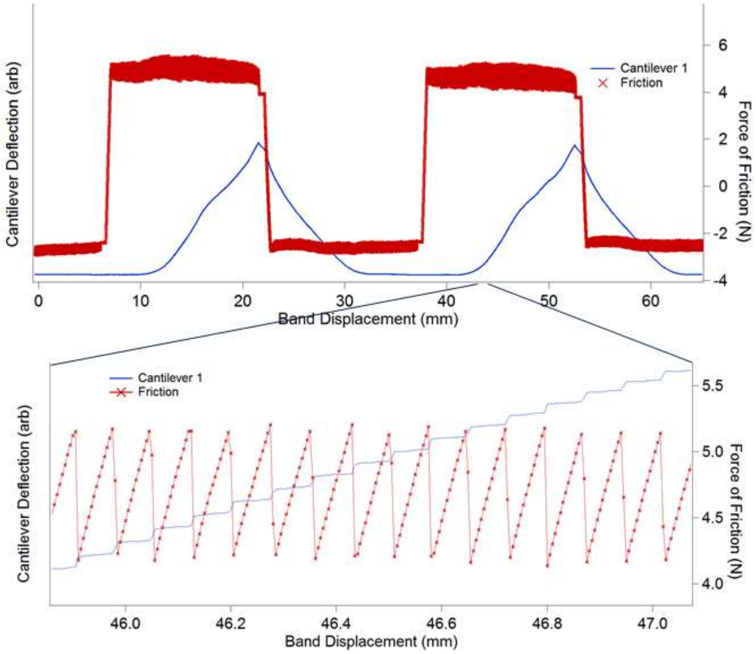

Fig. 8. Stick-slip phenomena observed in both load cell and cantilever measurements. Stick slips are sudden movements of the band on the order of 0.1mm that are observed at slow displacement speeds. The stepwise cantilever movements support the stick-slip observation.

V. CONCLUSION

We have developed and tested a device to measure tribological, triboelectric and discharge phenomena of a band pulled across a stationary rod. Despite the coarse size, it can measure non-uniform charge distributions on the order of ~1mm, stick-slip movement, rate of field emission, and the signature of breakdown. Future upgrades to the device will include tuning the cantilever resonance frequency by stiffness or size in order to increase spatial and temporal resolution, adding more cantilevers to achieve a better instantaneous charge camera, and using a combination of simulations and measured data to predict the details of charge distributions. Future experiments will also aim to uncover the relationship between friction and tribocharging by separating electrostatic and Van der Waals components to the frictional force.

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