Effect of Surface Texture on the Output Performance of Lateral Sliding-Mode Triboelectric Nanogenerator

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Abstract. In the working process of textured sliding-mode Triboelectric Nanogenerator (TENG), triboelectrification and wear occur simultaneously. At present, there is no systematic research on how the size of surface texture affects surface wear and output performance. In this paper, polymer surface with cylindrical texture of different pitches was prepared by photolithography and replication technology. According to the experimental results, the relationship between surface charge density and normal load of textured PI films was determined. Then the wear and electrostatic field of textured sliding-mode TENG were simulated by finite element method. The results show that the surface charge density increases with the contact load. And the open-circuit voltage of the sliding-mode TENG increases with the sliding distance given in this paper. The reason is that the height of textures in the separation zone is higher, which is caused by the shorter in-friction time and less wear, leading to the increased contact load in the next full-contact state. Therefore, more charges caused by the increased contact load tend to induce the higher output voltage. Moreover, textured surface with small pitch has better wear resistance and output characteristics. This research can provide an analytical method and basis for designing of surface texture in sliding-mode TENG.

1. Introduction
The Triboelectric Nanogenerator (TENG) is energy collector based on triboelectric and electrostatic induction. Because of its continuous power supply for portable electronic devices and distributed sensors, it has become a research hotspot for scholars at home and abroad [1, 2].

TENG can be divided into four basic working modes, vertical contacts-separated mode, lateral sliding mode, single-electrode mode and freestanding triboelectric-layer mode. Studies have shown that micro-/nano-texture processing on the polymer surface of vertical contacts-separated mode TENG can increase the contact area and thus increase the total surface charge of TENG [3, 4]. However, for lateral sliding mode TENG, friction and wear are also accompanied in the process of contact with electricity. Although the existence of texture has been proved to be effective in anti-wear resistance reduction in literature [5], systematic studies have not yet been conducted on how texture size affects the wear resistance characteristics of the surface or even the electrical output of TENG. The electrical properties of lateral sliding mode TENG have been studied in relevant literatures, but the textured surface is simplified to a smooth surface in the simulation studies [6, 7]. It is unable to provide guidance for the surface texture size design.
Therefore, Firstly in this paper, Polyimide (PI) films with different pitch were prepared in this study. By measuring the transfer charge of lateral sliding mode TENG composed of PI films, the relationship between surface charge density and normal load could be obtained. Secondly, the wear, stress-strain field and electrostatic field of textured surfaces with different pitch were simulated by the finite element analysis method, which can explore the effect of polymer surface texture size on the output performance of lateral sliding mode TENG.

2. The theoretical and simplified model

2.1. The theoretical model

Fig. 1 shows a lateral sliding mode TENG composed of a metal electrode and a polymer film. Among them, the material of metal electrodes is copper foil, its thickness is $H_1$, the elastic modulus and poisson ratio of it is $E_1$ and $v_1$. The polymer film material is PI, its thickness is $H_2$, the elastic modulus and poisson ratio of it is $E_2$ and $v_2$. The texture shape is a cylinder, and the diameter, height and pitch of the cylinder texture are $d$, $h$ and $w$, respectively. The surface density of the textured surface is denoted as $\alpha$.

When the generator is running, the back electrode and polymer film are fixed, the contact electrodes reciprocating sliding along the horizontal direction, with a constant load $F$ is applied to the top surface of contact electrode. The maximum separation distance of this model is $L$, the surface texture can be divided into separation zone and non-separation zone. The normal load in separation area texture is denoted as $F_{\text{Sep}}$, the total length of reciprocating sliding distance is denoted as $S$.

When the metal Cu is in contact with the polymer PI, due to different electron binding ability, electrons will transfer on the contact interface. So that the surface of PI is negatively charged and that of Cu is positively charged, as shown in Fig 1(a). When the contact material is separated laterally, the corresponding charge is induced at the back electrode, resulting in a potential difference between the two electrodes, as shown in Fig 1(b). The total transferred charge between electrodes under short circuit condition is denoted as $Q$, and the surface charge density is denoted as $\sigma$.

![Figure 1](image-url)

**Figure 1.** Schematic diagrams of contact-sliding mode TENG (a) in full contact; (b) in separation.

2.2. The contact and wear model

ABAQUS finite element software can simulate the contact deformation and wear of two contact surfaces in the process of reciprocating sliding, but the simulation of the real textured surface still needs to be simplified. Taking the textured film with pitch of $w=5\text{nm}$ as an example, the actual model has a cylinder number of 2500 and 1500 in the direction of length and width, respectively. If a real physical model is built, it needs to divide up to tens of millions of meshes in the finite element calculation, which seriously exceeds the computing power of the computer. Since the distribution of texture contact deformation
meets the periodic boundary condition along the z-axis, in order to save calculation time, single row texture can be intercepted on the texture surface for analysis with symmetrical boundary condition set on the side surface. Fig. 2 is a simplified finite element simulation model. The boundary conditions are set as follows: the bottom surface of the back electrode is fixed; the top surface of the contact electrode is coupled with reference point RP of six degrees of freedom; normal load and motion control are applied to the reference point RP.

Figure 2. Finite element model of contact mechanics.

Wear simulation adopts Archard formula, whose form is [8]:

\[ \frac{V}{S'} = K \frac{F}{H} \]  

(1)

Where \( V \) represents the wear volume, \( S' \) and \( F \) denote the slip distance and normal load, respectively. \( K \) and \( H \) are wear coefficient and brinell hardness of the material, respectively. When the wear process is simulated, the wear depth of each node involved in the contact of the polymer surface needs to be figured out. Eq. (1) can be rewritten as differential form. Denoting the linear wear coefficient \( KL=K/H \), the wear depth of the node in the incremental step can be written as:

\[ \Delta h = Kp \Delta s \]  

(2)

Where \( \Delta h \) and \( \Delta s \) are the wear depth and contact sliding distance of the node, respectively. \( p \) is the contact pressure at the node position. The wear simulation is realized through the following steps: (1) the contact stress at each node of the contact interface is obtained through the contact mechanics simulation, (2) in the wear subroutine, according to Eq. (2), the wear depth is calculated from contact stress and slip distance, (3) update the node position along the normal direction of the polymer contact surface to the actual position after wear, and enter the next round of wear simulation. The node displacement is realized by the Arbitrary Lagrange-Euler Method (ALE) in ABAQUS software. In order to avoid mesh distortion after adjusting the position of grid nodes, adaptive mesh smoothing is performed after the structural equilibrium equations have converged. During each mesh sweep, nodes in the domain are relocated and the new coordinates of nodes are determined by Eq. (3).

\[ R_i = R_i + u_i = N^N R_i^N \]  

(3)

Where \( R_i \), \( R_i^N \) and \( R_i^{N+1} \) are the position coordinates of the node before and after the adaptive adjustment, respectively. \( u_i \) represents the displacement of the node during the adjustment. \( N^N \) is the weighted function of the mesh smoothing algorithm.
2.3. The electrostatic induction model
Fig. 3 shows the electrostatic field simulation model built by COMSOL software to calculate the open circuit voltage of sliding TENG. The surface charge density of the upper surface of the cylindrical texture in the separation zone is determined by the experimental and contact mechanics simulation results. The surface of the two electrodes was set as suspended potential, the initial charge of the contact electrode was set as $Q$, with the polarity was positive. The electrostatic field boundary is set to earthing.

![Finite element model of electrostatic field.](image)

3. The experimental methods
The experimental device of lateral sliding mode TENG is shown in figure 4 (a), which is mainly composed of loading module, driving module, measurement module and data processing module[9]. The load module controls the normal load between the friction pairs, and the drive module controls the reciprocating motion of the slider. The measurement module measures the electrical output and friction force during the experiment by electrometer and force sensor respectively, and saves the results to PC for subsequent analysis.

![Testing apparatus (a) Schematic diagram of the Testing rig; (b) SEM image of textured surface.](image)

The preparation process of cylindrical texture of PI film is as follows, (1) the silicon template is prepared by lithography and wet etching, so that the surface of the silicon template has cylindrical pits with different spacing, (2) spin PI solution onto the surface of the processed silicon template and heat cure, (3) PI film with cylindrical texture was obtained by uncovering the film and cut into a rectangle block of 25mm×15mm. The SEM diagram of textured films processed is shown in Fig. 4 (b).
The experiment was conducted at room temperature, and the average speed of the reciprocating motion of the slider was 16 cm/s. When the normal load $F$ is 4N, 8N, 12N and 16N, respectively. The charge $Q$ of the polymer surface reaches saturation after multiple contacts is recorded.

4. Results and discussion

As mentioned above, the simplified model shown in Fig. 2 and Fig. 3 is simulated. The specific parameters are set as follows: the length of the metal electrode and the polymer film $L=375\mu$m, the width $W=225\mu$m, the thickness of the metal electrode $H_1=100\mu$m, and the thickness of the PI film $H_2=80\mu$m. Texture diameter $d=5\mu$m, height $h=3\mu$m, and spacing $w$ is 2$\mu$m, 5$\mu$m and 10$\mu$m, respectively. In the wear simulation, the uniform pressure applied on the upper surface of the contact electrode is $p=16N/(25mm \times 15mm)= 42.67kPa$. Elastic modulus, poisson ratio and dielectric constant of metal electrode material are $E_1=119GPa$, $\nu_1=0.326$ and $\varepsilon_1=100$, respectively. Elastic modulus, poisson ratio and dielectric constant of polymer material are $E_2=2.9GPa$, $\nu_2=0.34$ and $\varepsilon_2=3.4$, respectively. Set the friction coefficient at the contact interface as equals to 0.3, and set the line wear coefficient as $K=1.359 \times 10^{-14}m^3/(N\cdot m)$.

4.1. Effect of the pillar pitch and load on the charge density

Firstly, through the lateral sliding mode TENG test platform, the contact charges $Q$ of textured PI films with different pitch under different normal loads $F$ was obtained.

In this paper, there was no significant wear on the polymer surface during the experimental measurement, the height of polymer surface texture was highly consistent, the contact state was the same, and the average surface charge density $\sigma=Q/(\alpha S_1 W)$ in the PI thin film separation zone. The surface charge density of textured films varies with the load $F$, as shown in Fig. 5. The surface charge density of textured films at different distances increases with the increase of the load $F$. The reason is that the increase of the load promotes the close contact between the two contact surfaces, so the surface charge density increases accordingly [10, 11]. Under the same pressure, the textured surface with larger spacing has higher surface charge density. The reason is that the increase of spacing reduces the texture density of PI film, while the increase of load on each texture increases the surface charge density. The relationship between surface charge density and load can be obtained by linear fitting test data.

![Figure 5. The relationship between the charge density with normal load.](image)

$$\sigma=\begin{cases} 4.46F + 32.73 & w=2\mu m \\ 10.69F + 57.04 & w=5\mu m \\ 15.54F + 144.55 & w=10\mu m \end{cases}$$

(4)

4.2. Effect of the pillar pitch on the wear resistance

In this section, through ABAQUS simulation software and the wear subroutine written by ourselves, the finite element simulation of reciprocating sliding wear on textured surfaces with different spacing is
carried out. The maximum wear depth of textured surface varies with sliding distance at different intervals.

Now take the pitch \( w = 2 \mu m \) textured surface as an example to analyze the wear of texture at different locations. A total of 53 textures height is the same at initial time, and the variation \( h \) of texture depth at different positions after the reciprocating sliding distance \( S = 0.6m \) is shown in Fig. 6. The wear depth of texture in the separation zone (texture number 1-21) increases with the increase of texture number, but the wear depth of texture in the non-separation zone is approximately the same. The reason is that the texture of the separation zone will separate in the process of reciprocating sliding and shorter in-friction time, so the wear amount is small.

![Figure 6. Wear depth of texture at different positions.](image)

The texture at the junction of the separated zone and the non-separated zone has the maximum wear depth. The maximum wear depth of textured surfaces with different pitch increases with the sliding distance, as shown in Fig. 7. The wear depth of textured surfaces with different pitch increases with the sliding distance \( S \). The wear depth of textured surface with small pitch \( w \) is relatively small. At the same sliding distance (such as sliding distance \( S = 0.6m \)), the topography of each textured surface after wear is shown in the illustration in Fig 8. The gray shaded part represents the part where is removed (in the illustration, the wear amount is magnified 500 times in the diagram for convenience of comparison). The textured surface with pitch of \( w = 10 \mu m \) is much higher than that of other textures.

![Figure 7. The relationship between the wear depth and the sliding distance.](image)

**4.3. Effect of the pillar pitch on the open-circuit voltage**

In this section, the open circuit voltage of textured surface with different sliding distances is simulated and analyzed by finite element analysis.

Through wear simulation, the stress and strain field of textured surface after wear is obtained. The contact stress distribution of textured surface after wear is uneven due to different wear depth. However, since the open circuit voltage value is only related to the charge density of the textured surface in the
separation zone, the contact load of the simplified model is equivalent to the normal load relation in the actual model as \( F = 25\text{mm} \times 15\text{mm} \times \frac{F_{\text{sep}}}{SW} \).

The variation of open circuit voltage with sliding distance of different pitch is shown in Fig. 8. The results show that the open circuit voltage increases with the increase of sliding distance in the textured model with different spacing, which is consistent with the trend of the first stage of experimental results in the literature [9]. The reason lies in the uneven wear of textured surface, which is characterized by small wear and higher texture in the separation zone. When the texture is in full contact again, the load borne by the texture in the separation zone increases, which increases the surface charge density and outputs open-circuit voltage. At the same sliding distance, the textured model with smaller pitch has higher open circuit voltage, because the textured model with smaller pitch has higher surface density, which is conducive to generating more contact charges, so the open circuit voltage is higher.

![Figure 8](image_url)  
Figure 8. The relationship between the open-circuit voltage and sliding distance.

5. Conclusion

Based on the experimental and simulation study on the output characteristics and surface wear of textured lateral sliding mode TENG, the main conclusions are drawn as follows:

1. Textured surface wear simulation shows that, under the same normal load, reducing the pillar pitch can reduce the surface wear and improve the wear resistance of textured surface. The reason is that the smaller pitch increases the texture density and reduces the contact stress.

2. The electrostatic field simulation of textured surface shows that, under the same normal load, reducing the pillar pitch can improve the open-circuit voltage and improve the electrical performance of textured surface. This is because the reduction of pitch can increase the surface density of the texture, more contact area increasing the amount of surface transferred charge and the output higher open circuit voltage.

3. Experimental and simulation studies show that the amount of sliding TENG transfer charge increases with the sliding distance. In the given range in this paper, the open-circuit voltage of the generator increases with the increase of the sliding distance, which is caused by the uneven wear on the surface of the polymer film due to the different distances involved in the sliding friction, which increases the textured contact load in the separation zone and produces more transfer charges.

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