A novel method for analyzing electrification in friction process

TianHai Chang, JinCheng Wu
School of Electronic and Information Engineering, South China University of Technology, Guangzhou 510640, Guangdong, China
E-mail: wujinc@163.com

Abstract. This paper is trying to explore the electrification mechanism of solid material during the friction process in a new angle of secondary electron emission characteristics, and explain the course of electrostatic formation by using the SEE (Secondary electron emission) theory. It will demonstrate that there is a positive connection between SEE yield and the cause of electrostatic electrification by conducting the experiment with the SEE theory. We are going to show the part which SEE characteristics will take in electrification, and deduce a new formula model with SEE yield and electrostatic potential by using our experimental data, which demonstrates that there is a numerical relationship between them. Based on the conclusion from this experiment, it can provide a new thought for electrostatic theory development of solid material and analysis on some special electrification phenomena.

1. Introduction
Early about 600 years BC, materials electrification by friction was discovered by Thales from Greece. However, how to explain these phenomena scientifically, especially for micro-mechanism of electrification, is still one of knotty problems in the present field. As we know, there are various viewpoints and theory in academic circles [1]. One theory which is widely accepted is “contact-separate” theory that is based on material contacting and separating course, combining the energy band theory as a model. This theoretical system has provided a reasonable explanation for mechanism of electrification process of materials, including solid, liquid and gas. However, in variety of complicated electrification processes, many experiment phenomena can’t be explained satisfyingly, which is needed us to study further. Based on above analysis, this paper is going to try to explain the course of electrostatic formation by using the SEE characteristics and considering SEE yield as a key factor in analyzing electrification process of solid materials. The theory of SEE should give a better explanation to some special electrification phenomenon and we plan to introduce the formula model of SEE to demonstrate the relationship between SEE yield and surface potential.

2. Secondary Electron Emission Theory

2.1 SEE phenomenon
Electrons (or ion) will be forced to excite out from material when the primary incident electrons (or ion) possessed of some energy or speed have bombarded materials’ surface, which are called SEE(Secondary Electron Emission). Early in 1899, Campbell had discovered this phenomenon. The electron bombarding material is usually called original electron (or primary electron), on the other
hand, what is emitted from material’s surface is called secondary electron. The secondary electron with less than 50eV is usually called true secondary electron, besides, there are other electrons, including inelastic scattering, elastic scattering and auger electrons and so forth [2]. The true secondary electron takes a large part in this process. So, it is the main object we must study on. The model of secondary electron emission is showed in figure 1.

![Figure 1. Secondary electron emission model.](image1)

2.2 Secondary Electron Emission Yield
The capacity of SEE is usually presented by SEE yield $\delta$. Simply, SEE yield is defined by the radio of SEE stream $I_s$ and original incident electron stream $I_p$ [3], this relationship can be described in formula 1.

$$\delta = \frac{I_s}{I_p}$$ (1)

![Figure 2. The classic relationship curve between SEE yield and incident energy.](image2)

Further, there is a close relationship between the amount of original electron and $\delta$ with the characteristic of bombarded material in the special environment conditions. The figure 2 is classic secondary electron emission characteristic curve of solid material [4].

3. Friction Electrification Experimental Scheme

3.1 Experimental Materials
Three solid materials are chosen for this experiment, including polyvinylchloride (PVC), high-density polyvinylchloride (HDPE) and polypropylene (PP). Their characteristics are listed in table 1 [3], and their shapes are showed in figure 3. We mainly choose the circle one as the analysis object of this experiment.
Table 1. Experimental material characteristic.

| material | BRRR<sup>a</sup> /Ω·m | BRRM<sup>b</sup> /Ω·m | SRM<sup>c</sup> /Ω | MSY<sup>d</sup> /δ | COE<sup>e</sup> /eV |
|----------|-------------------------|-------------------------|-----------------|-----------------|-----------------|
| HDPE     | $10^{13} \sim 10^{14}$ | $>10^{14}$              | $4.26 \times 10^9$ | 2.71            | 250             |
| PP       | $10^{14}$               | $>10^{14}$              | $2.53 \times 10^{11}$ | ——              | ——              |
| PVC      | $10^{14} \sim 10^{15}$ | $>10^{14}$              | $1.53 \times 10^{12}$ | 2.12            | 400             |

<sup>a</sup> Body resistance ratio reference value  
<sup>b</sup> Body resistance ratio measure value  
<sup>c</sup> Surface resistance measure value  
<sup>d</sup> Maximum SEE yield  
<sup>e</sup> Corresponding original electron

Figure 3. Schematic diagram of materials in friction experiment.

3.2. Design of Experimental Scheme

The experiment is conducted by using self-designed equipment “electrostatic dynamic measurement device”, whose structure is showed in figure 5. A3 carbon steel is fixed on the base as a friction object, which rubs with above three materials by turns. From this experiment, we have gotten three groups of data by using the keen probe under different speeds which are showed in the table 3. Otherwise, some critical environment conditions are listed in table 2 (in the vacuum environment, the electric field and magnetic field are shielded.). To ensure the accuracy of this experiment, every material should be polished and cleaned carefully before experiment in order to eliminate electrostatic accumulated on the surface [5, 6].
1. Variable-Frequency Motor 2. rotation bearing 3. rotation friction disc 4. test material 5. static friction disc 6. probe clamp 7. force application bearing 8. workshop 9. humidity probe 10. force weights 11. Manipulator 12. electrostatic probe 13. signal lines 14. temperature probe 15. humidity control panel 16. temperature control panel 17. probe interface 18. Acquisition Card 19. ESB interface 20. computer 21. Cabinet

Figure 5. Electrostatic dynamic potential measurement device.

Table 2. The experimental conditions of three materials.

| RH° | E.T.° | Spd.° | FP° | PD° | S.T.° | BM° | RM° | DM° |
|-----|-------|-------|-----|-----|-------|-----|-----|-----|
| (80±5)% | 27.6 | 70-150 | 5 | 2 | 3 | A3 carbon steel | PVC | HDPE, PP |
| % | | | | | | | PVC, HDPE, PP | |

Relative Humidity; Environment Temperature; Rubbing Speed; Friction Pressure; Probe Distance; Sampling Timing; Base material; Rotating materials; Detected materials

Table 3. Electrostatic potential data of three materials in friction experiment.

| Speed r min⁻¹ | Maximum value | Minimum value | Average(absolute) |
|---------------|---------------|---------------|-------------------|
| PVC | HDPE | PP | PVC | HDPE | PP | PVC | HDPE | PP |
| 30 | 0.0782 | 0.6211 | 0.7328 | -0.5018 | -0.2924 | -0.2687 | 0.0798 | 0.1585 | 0.0297 |
| 50 | 0.0391 | 0.6211 | 0.0977 | -1.3288 | -0.4805 | -0.3175 | 0.2749 | 0.2548 | 0.0417 |
| 70 | 0.0391 | 0.5942 | 0.7328 | -1.5246 | -0.6417 | -0.5129 | 0.3678 | 0.3841 | 0.1031 |
| 90 | 0.0391 | 0.5674 | 0.7084 | -1.4851 | -0.7223 | -0.6106 | 0.3869 | 0.4736 | 0.1488 |
| 110 | 0.0391 | 0.7084 | 0.7084 | -1.4851 | -0.6595 | -0.6595 | 0.3615 | 0.4973 | 0.1752 |
| 130 | 0.0391 | 0.5674 | 0.7328 | -1.5633 | -0.7761 | -0.6839 | 0.4336 | 0.4897 | 0.1727 |
| 150 | 0.0391 | 0.5405 | 0.7084 | -1.7192 | -0.8835 | -0.6351 | 0.4308 | 0.5298 | 0.1576 |

4. The Experimental Result and Phenomenon Analysis
We make a contrast among the three groups of electrostatic potential data from table 3, the curve is painted in figure 6.
From figure 6, we can find out a peculiar phenomenon that the electrostatic potential in Y axis does not increase with the rubbing speed in X axis all the time, especially when the speed reaches to some value, potential of PP and HDPE even has a trend of decrease at the speed value closing to 140 r min\(^{-1}\). This phenomenon is not what we expect before. Because, based on the energy band theory model, rubbing process of materials is equivalent to countless contact point being the “contact-separate” status. At the same time, friction work will produce heat on material surface, which can be conducted into inner of material. As a result, some electrons will be emitted by heat to transit up to different energy band. Take the insulator for instance, electrons from the inner are excited to span forbidden band to arrive at empty band and finally become free ones. When energy they have is double to work function (minimum energy of electrons coming out of the solid inner) of materials they come from, free electrons will get rid of constraint and reach to the surface, at the end, electric double layer will be created gradually. Finally, two friction materials will get the inverse charge as soon as they separate.

In the experiment, according to energy band model in figure 7, with the increase of rubbing speed, more heat will be produced on the material surface which can evidently add the number of electrons coming out from materials. These electrons with enough energy will span over the energy band to become free ones. As a result, electrostatic potential goes up more when rubbing materials separate [1, 7]. However, the result from experiment does not accord with what we expected. So we are planning to introduce SEE characteristics to analyze it in this situation. We will simulate the course of electrification at the angle of SEE characteristics, just like figure 8 showed below.
We try to take SEE yield consider as one of critical factors in the process of electrostatic electrification. At first, referring to figure 2 and table 1, SEE yield is not rising with the increase of original energy \( E \) on the whole. From the beginning of Y axis of figure 2, SEE yield \( \delta \) climbs up rapidly, and then reaches the maximum value \( \delta_m \) when \( E = E_m \), after that, \( \delta \) turns to decline. According to the definition of SEE yield, the process of \( \delta \) from up to down exactly reflects a trend of the number of electrons excited by incident electrons, which will affect the account of electrostatic potential when rubbing materials separate. We can analyze this experimental result as follows: materials rubbing with each other will produce more heat energy as well as inner electrons [7, 8, 9]. This result will lead to the increase of the number of incident electrons on the surface of materials. This changing process can be analyzed by dividing into two parts: part 1, for some specific SEE yield of material, when original energy \( E < E_m \), the number of secondary electrons excited by rub heat energy will rise quickly, which leads that surface electrostatic potential goes up much; part 2, when original energy \( E > E_m \), from the curve showed in the figure 2, SEE yield \( \delta \) is keeping a rapid decrease trend, which caused that the number of electrons aroused by heat rises slowly, or even goes down, as well as electrostatic potential, at the end it gradually reaches to a dynamic balance value [11, 12]. We can describe this change by using two simple flow charts below. In the case of \( E < E_m \), \( \delta \) goes up with a large slope, the whole changing process of potential will be showed in figure 9.

![Figure 9](image9.png)

**Figure 9.** The verified process of surface potential when \( E \leq E_m \).

On the other hand, when \( E > E_m \), the value of \( \delta \) goes down, the above changes will be showed in figure 10 below.

![Figure 10](image10.png)

**Figure 10.** The verified process of surface potential when \( E > E_m \).

5. Friction Electrification Formula Model with Secondary Electron Emission Yield.
From above analysis of experimental result, adding up the changing process description in figure 9 and figure 10, among some limited energy area of incident energy, we can probably get the special relationship between incident energy and electrostatic potential on the material surface which can be drafted in the figure 11.
Figure 11. The relationship between original energy and surface electrostatic potential of rubbing material.

Electrostatic potential of materials during rubbing process begins to rise slowly when incident energy $E$ reaches to $E_1$, and at the end it will reach to dynamic balance value $V_m$. According to the figure 11, we probably get a related formula:

$$V = k_1 \cdot \arctan(k_2 \cdot E)$$

(2)

$V$ represents electrostatic potential of materials and $E$ as the incident electron energy, $k_1$ and $k_2$ are relevant coefficients which are decided by characteristics of and SEE yield of materials. Formula 2 unites semi-empirical formula 3 [3, 13, 14], which gets:

$$\delta(E)/\delta_m = 1.526 [1 - \exp(-z^{1.725})] / z^{0.725} \quad (z = 1.284E/E_m)$$

(3)

A new formula model will be established with electrostatic potential and secondary electron emission in this process of dynamic friction.

$$\begin{cases}
\delta/\delta_m = 1.526[1 - \exp(-z^{1.725})]/z^{0.725}, \quad z = 1.284E/E_m \\
V = k_1 \cdot \arctan(k_2 \cdot E)
\end{cases}$$

(4)

Simply, the relationship model with secondary electron emission yield and electrostatic potential is showed by a formula 5 below.

$$\delta/\delta_m = 1.526[1 - \exp(-z^{1.725})]/z^{0.725},$$

and, $z = 1.284 \cdot \frac{1}{k_2} \cdot \tan(V/k_1)/E_m$

(5)

Therefore, the maximum value $\delta_{m}$, incident energy $E_m$ and related coefficient $k_1$ and $k_2$, which are relative stable for some special solid materials. So, based on the formula 5, we can conclude that the difference of SEE yield of material has a special relationship with electrostatic potential. As a result, we think that it is feasible to analyze the changing process of electrostatic potential on material surface at the angle of SEE yield and benefit to expand the thought of studying the electrostatic theory further.

6. Conclusion

It is a novel method to study the process of electrostatic electrification with SEE yield. And the following conclusions can be drawn:

(1) Based on the intrinsic “contact-separate” theory and energy band model, study of electrostatic theory with the characteristic of SEE contributes to comprehend understanding of electrification mechanism. The phenomenon occurred on this experiment reflects the characteristic presentation of SEE. According to this relationship between them, we can deduce the micro process of electrostatic generation and it also shows the changing trend of electrostatic potential value. Formula 5 also has
revealed some numerical connection between $\delta$ and $V$.

(2) It helps us to analyze electrostatic generation and electrostatic discharge by the formula model with $\delta$ and $V$. As long as SEE yield of materials can be measured, we could generally estimate the dynamic electrostatic potential during the process of friction, which is benefit to the prediction of high electrostatic voltage level and helps us to take a necessary measure to avoid an electrostatic accident ahead of time.

(3) By using the relationship between $\delta$ and $V$, we can change the characteristics of SEE of material in order to decrease electrostatic voltage efficiently during the process of practical production environment and lower the accident incidence in practice. In conclusion, it is useful to understand deeply the micromechanics of electrostatic formation in the inner of material and provide a full new method of electrostatic protection technology through introduction of SEE yield during the rubbing process between solid materials.

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