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A Novel Material Identification Method Based on Material Surface Static Electricity Discharge

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In this paper, a novel material identification method based on material surface static electricity discharge is introduced. The induced charge model between charged material and a metal electrode is established at first. The process of accelerated discharge of material surface charge through metal electrode is studied. Then the electrostatic signal acquisition system with a special structure is designed. Five typical materials, aluminium, glass, paper, wood and polytetrafluoroethylene (PTFE) are measured. The attenuation speed of material electrostatic signal is represented by feature values which consist of the discharge factor and signal peak variance. Then the k nearest neighbor classification algorithm is used to identify and classify the five kinds of materials. The results show that average recognition accuracy rate of the five materials is 83 %. This method could be used in the materials identification.

Keywords: material identification, static electricity, discharge, k nearest neighbor (KNN) classification.

1. INTRODUCTION

It is an extensive and deep researched topic to identify the categories and components of the material accurately. These identification technologies and methods are widely used in the material composition analysis [1, 2], and the robot tactile sensor [3]. The current automatic material identification methods are mainly based on the machine vision sensor [3, 4] and the contact sensor based on the principle of thermal sensation [5], electrostatic or piezoelectric [6]. Although the machine vision method has a wide range of recognition and simple test principle, it is unable to accurately obtain the texture and color information of materials when the light conditions are not ideal, especially in dark conditions. In that case, it is almost impossible to identify materials. In contrast, various contact sensors can obtain more accurate results by directly measuring the material properties such as texture, hardness, dielectric constant and so on.

Material identification based on electrostatic measurement is a new method of contact measurement. The Wolfson electrostatic laboratory use the Faraday bucket and electrometer to measure the amount of charge and polarity of different polymer materials and textile samples after controlled friction, and effectively identify more than ten kinds of fiber materials [7]. Kimoto A. [8] measured the induced charge signal of electrode in the process of contact, and then distinguished the specific material according to the electrostatic signal. By using electrostatic and piezoelectric composite sensor, their subsequent studies measured the hardness of the material and the amount of charges, finally achieving more than ten kinds of materials and the effective identification of hardness [9]. In the area of material identification by electrostatic method, most of researches are mainly through the detection of the amount of charge carried by the material. However due to the complexity of the environmental conditions, the surface charge of the material is not a stable parameter in different environments, and the induced charge will also change, therefore methods based on the amount of charge are not always accurate.

In this paper, a special electrostatic sensor structure design and material identification method are proposed. The proposed method is based on the discharge characteristics of the surface charge rather than the absolute value of surface charge. The electrostatic signals of five typical materials were collected and analyzed. Two features of the electrostatic signal are extracted, and the classification algorithm is designed. Finally, the recognition and classification of five kinds of materials are realized by this method.

2. MEASURING PRINCIPLE

According to the classical theory of electrostatic contact separation, the fundamental reason of electrostatic electrification is the result of the contact and separation between objects [10]. In the natural state, if the electrification process is no longer continuing, the static electricity on the object will gradually disappear after a period of time due to the attenuation or dispersion of charge. Charge decays mainly through charge neutralization and leakage. The charge leakage usually releases the charge to the ground. And the nature state of leakage is affected by the resistivity of the medium, the dielectric constant and the environmental conditions.

In this paper, a novel measurement structure is designed, which is made up of a grounded metal electrode and an isolated conductor material, and the surface charge of the material will be rapidly introduced into the ground through the metal electrode, which can accelerate the discharge of the static electricity. Electrostatic measuring

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circuit connected between metal electrode and ground will be able to measure the amount of charge flowing into the ground. The measurement principle is shown in following Fig. 1.

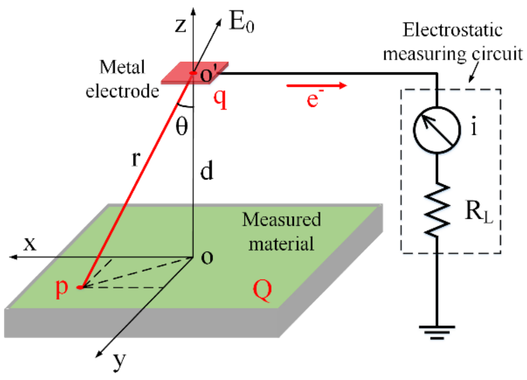

Fig. 1. Measurement model of induced current

In this paper, it is assumed that Q is the uniformly distributed charge on the material surface, and S is the effective area of the material model. Then, the charge density of the material surface is $\sigma = Q/S$. A metal electrode is arranged above the measured material, which the equivalent area is s. The distance between material surface and electrode is d. Therefore, the electric field of material surface charge can be regarded as the combined effect of a limited number of point charges on the surface. Then, for a point charge p, when the distance between the p and the metal electrode is r, the electric field intensity formed by point charge p at the center of the metal electrode can be expressed by the following equation:

$$E_0 = \frac{k\sigma}{r^2}, \tag{1}$$

where k is the electrostatic force constant.

The space coordinate system is established as shown in Fig. 1. The material surface center point o is defined as the origin of coordinates, and the xy-plane as the material surface. The metal plate center is on the z axis. Due to the model symmetry, the electric field intensity formed by all point charges is perpendicular to the metal electrode. Therefore, the total electric field intensity is defined by following equation:

$$E = \iint_S E_0 \cos\theta \mathrm{d}S = 4k\sigma \int\int_0^{\frac{\sqrt{S}}{2}} \frac{d}{\sqrt[3]{\left(d^2+x^2+y^2\right)^2}} \mathrm{d}x\mathrm{d}y \tag{2}$$

According to Gauss's theorem, the charge density on the surface of p point metal plate can be obtained:

$$\rho = \varepsilon_0 \varepsilon_r E. \tag{3}$$

As the metal electrode is far less than the material, when the metal electrode equivalent area is s, the inducted charge q on the metal electrode can be described as following

$$q = \rho s = \varepsilon_0 \varepsilon_r E s. \tag{4}$$

If the metal electrode gradually approaching to the measured material surface from the top, the electric field changes, which results in the change of induced charges on the metal electrode. If the metal electrode is connected to the ground by an electrostatic measuring circuit, then the induced current will be generated in the circuit. In order to sustain the induced current signal, it is necessary to keep the movement of the metal electrode. Therefore, in this model, the reciprocating motion of the metal electrode on the measured material is designed, which makes the electrode contact with the measured material repeatedly, so the distance d between electrode and material can be expressed as

$$d = \frac{D}{2}(1 + \cos 2\pi f t), \tag{5}$$

where D represents the maximum distance between the material surface and electrode, and f is the frequency of contact-separation device motion during the time period which starts at the moment when the electrode is at maximum distance and ends when the electrode returns to the same position. We combine Eq. 4 and Eq. 5, the induced current $i(t)$ would be expressed by following Eq. 6.

Assuming that the ground resistance between the conductor and the ground is R, and the ground capacitance is C, the surface charge of the conductor at any time is:

$$Q(t) = Q_0 e^{-\frac{t}{RC}}. \tag{7}$$

The equation shows that the charge of an isolated conductor satisfies the exponential decay law, the time constant is $\tau = RC$. It is clear that the isolation of isolated conductors from the ground by the use of insulating materials will be effective in slowing down the discharge of static electricity in the natural state of the conductor.

When the metal electrode is in contact with the measured material, because of the change of the surface resistance and capacitance to the ground, the static electricity on the material will add a fast discharge channel, that is, the static electricity flows through the metal electrode to the ground. At this time, the static electricity on the material will flow to the electrode at the contact time. When the electrode is separated from the material, the residual charge on the material will return to the isolated state. The contact state diagram is shown in the following Fig. 2.

$$i(t) = \frac{\mathrm{d}q}{\mathrm{d}t} = \frac{4k\varepsilon_0\varepsilon_r sQ}{S}\left[\mathrm{d}\left(\int\int_0^{\frac{\sqrt{S}}{2}} \frac{D\cos 2\pi ft + D}{\sqrt[3]{\left((D\cos 2\pi ft + D)^2 + 4x^2 + 4y^2\right)^2}} \mathrm{d}x\mathrm{d}y\right) / \mathrm{d}t\right]. \tag{6}$$

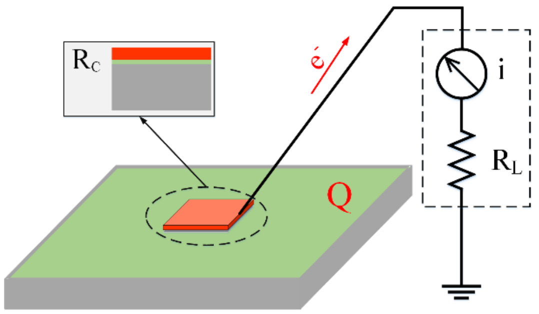

Fig. 2. The diagram of contact state

In Fig. 2 R_c represents the contact resistance between electrode and material. By assuming that the electrode and the material is in complete contact with certain contact pressure, and the contact spots is rectangular spot with side L, the contact resistance [11, 12] due to a rectangular spot of side L can be written

$$R_C \approx \frac{S(N)(\rho_1+\rho_2)}{2L}, \tag{8}$$

where $S(N)$ represents shape factor which is 0.8617. The ρ_1 and ρ_2 are the conductivity of the metal electrode and the measured material. So resistance and capacitance to ground of the measured material can be expressed as:

$$\begin{cases} R = R_c + R_L \\ C = C_c + C_L \end{cases}, \tag{9}$$

where R_L and C_L especially represent the equivalent resistance and capacitance of electrostatic measurement circuit. Therefore, the surface charge of the material under multiple contact measurement is satisfied by the following equation:

$$Q(n) = Q_0 e^{-\frac{nt}{RC}}, \tag{10}$$

where n represents the number of contacts, and $Q(n)$ represents the amount of charge on the surface of the material during the n time contact. The single contact time is t. Therefore, the discharge ratio of the material surface charge after each contact can be defined as the discharge factor α.

$$\alpha = e^{-\frac{t}{RC}}. \tag{11}$$

If the contact time and pressure are constant, the t and the minimum d will remain the same. Thus, the capacitance to ground is constant, and the discharge factor is mainly related to the resistance to ground. According to Eq. 6, resistance to ground is mainly dependent on the contact resistance.

Therefore, the induced current equation in the measuring principle is described in Eq. 12.

According to current equation and actual parameters, five kinds of discharge factors are selected as 0.8, 0.6, 0.4, 0.2 and 0.1 respectively. We amplify the induced current, and then convert it into voltage signal. Several kinds of electrostatic signals with different discharge factors are drawn by MATLAB. The electrostatic signals are shown in Fig. 3.

The result shows that with the decrease of the distance between the metal electrode and the measured material, the electric field intensity on the metal electrode is increased and the induced charge increases subsequently, thus, there will be a peak value in the electrostatic signal. Besides, with the decrease of the α, electrostatic signal shows a higher attenuation speed, which means the surface charge decrease more with lower discharge factor. Especially when the α is less than 0.2, the voltage signal only has a significant negative peak, which means that there is almost no static charge on the material surface after one time contact and separation.

Furthermore, because the amount of surface charge on the material will be partially introduced into the ground when the electrode is in contact, the induced current on the metal electrode is just the result of the residual charge on the material. Then, when the metal electrode is repeatedly contacted and separated from the material, the corresponding induced current will show a trend of attenuation. For different materials with different discharge factor, the discharge in the contact process will also be different.

$$i(t) = \frac{\mathrm{d}q}{\mathrm{d}t} = \frac{4k\varepsilon_0\varepsilon_r s Q_0 e^{-\frac{nt}{RC}}}{S}\left[\mathrm{d}\left(\int\int_0^{\frac{\sqrt{S}}{2}} \frac{D\cos 2\pi ft + D}{\sqrt[3]{\left((D\cos 2\pi ft + D)^2 + 4x^2 + 4y^2\right)^2}}\mathrm{d}x\mathrm{d}y\right)/\mathrm{d}t\right]. \tag{12}$$

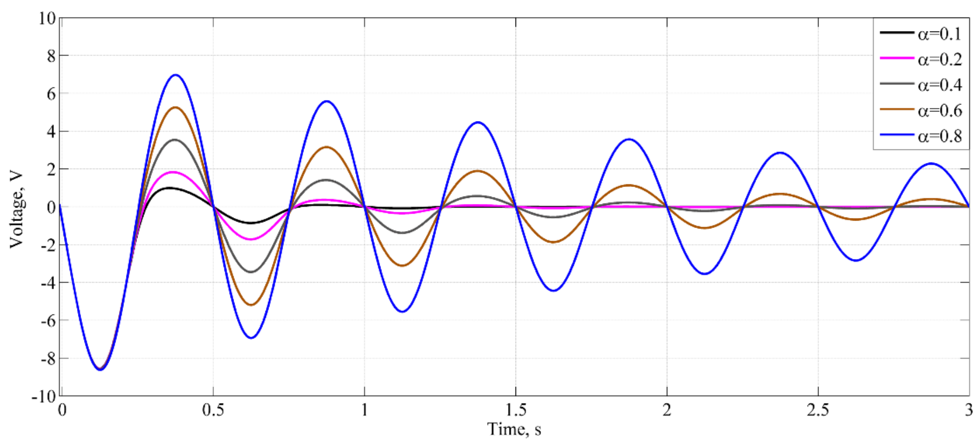

Fig. 3. Electrostatic signals with different discharge factors

Accordingly, through this measurement method, the electrostatic signals of different materials will show different attenuation speed, which can be used to distinguish different materials.

3. EXPERIMENTAL DESIGN

According to the measuring principle, we established the platform of the material surface electrostatic signal detection system as shown in Fig. 4. It is composed of the experimental platform, the reciprocating mechanical structure, the detection unit, the D.C. stabilized source and the high-speed A/D converter. The detection unit includes the electrode, the charge amplifier circuit, the I-V converter circuit and the low pass filter circuit. The output signals are stored by the LeCroy WaveRunner 6000A Oscilloscope, and then offline analyzed in the MATLAB software environment. Five kinds of typical materials are selected for signal acquisition and analysis, which are aluminum, glass, paper, wood and PTFE. The size of each material model is 5 cm × 5 cm × 2 cm. The environment temperature and humidity during the experiment were 20°C and 35 %, respectively.

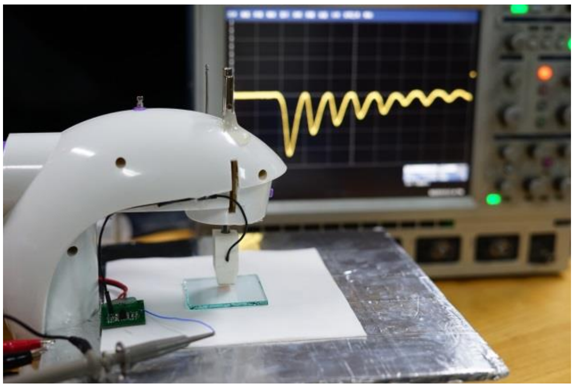

Fig. 4. Platform of the material surface electrostatic signals detection system

The metal copper foil (1 cm × 1 cm × 0.2 cm) is attached to the front end of the insulating electrode and then is mounted on a reciprocating mechanical arm. Five kinds of materials electrostatic signals were measured at a fixed motion frequency of 2 Hz. The sampling time is 3 seconds, and the sampling frequency is 5 kHz. 50 groups of signals are collected for each kind of materials. We intercepted three seconds duration signals, arranging the signals based on the attenuation speed. Five kinds of materials electrostatic signals are shown in Fig. 5.

The experimental results show that with decreasing of the distance between the metal electrode and material, the electrostatic signal increases gradually and then decreases to the initial value. When the electrode is far away from the measured material, the electrostatic signal also shows the characteristics of reverse increase and decrease. When electrode is periodically contacted and separated from material, the electrostatic signal also shows a periodic change.

Furthermore, we can see from Fig. 5 that the attenuation speed of the PTFE is the lowest, and there is no significant difference between the main negative peak and adjacent negative peak. It shows that there is almost no discharge on the PTFE surface after every separation. Compared with the aluminum, the electrostatic signal only has one obvious negative peak value, which indicates that there is almost no static electricity on the aluminum surface after one time contact and separation. Compared with the results of Fig. 3, we can know that the discharge factor of aluminum is the smallest, and the PTFE is the largest, so the attenuation speed of five kinds of material electrostatic signal indicates that the measured signal is in good agreement with the constructed signal according to the theoretical equation.

Moreover, the maximum negative peak of the electrostatic signal represents the maximum voltage of the electrode, which has not been contacted with the material. The adjacent negative peak value represents the signal value of electrode which is introduced by the residual charge after the first contact. Therefore, the ratio of adjacent negative peak value to maximum negative peak value indicates the degree of attenuation after the first contact and separation, which corresponds to the discharge factor in the theoretical model.

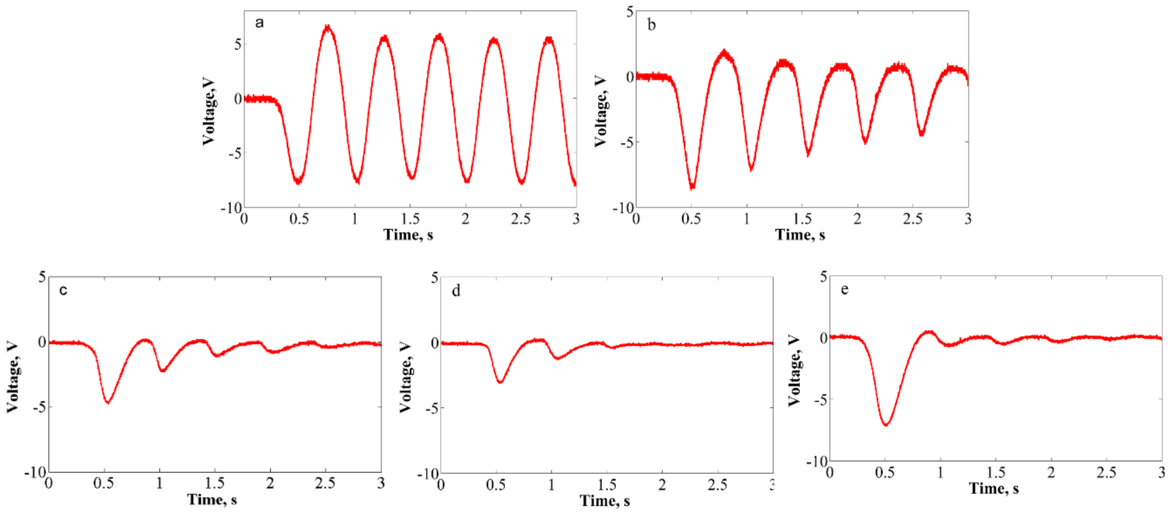

Fig. 5. Electrostatic signals of five kinds of materials: a – PTFE; b – glass; c – wood; d – paper; e – aluminum

In the following text, we will carry out the process of feature extraction, which is related to the electrostatic signals of different materials, and design the classification algorithm to carry out the identification and classification of the electrostatic signals.

4. MATERIALS RECOGNITION

4.1. Classification algorithm

K-Nearest Neighbours classification (kNN) is the simplest and most widely used learning method for classification [13]. In order to classify the feature vector X of an unknown material signal, first of all, kNN classification will respectively label the five kinds of road surface feature vector X_i (i = 1, 2, 3, 4, 5) with C_i (i = 1, 2, 3, 4, 5). Secondly, the Euclidean distance between the unknown material signal feature vector X and the feature vectors of all the signals in the training set will be calculated, and then the k material sample feature vectors with the nearest distance from the unknown material signal feature vector X can be obtained. Finally, the proportions of each material category in the k nearest material samples will be calculated, and the high proportion of material sample will be classified as unknown material sample.

4.2. Feature extraction

The measured signals show that the electrostatic signals of different materials reflect different attenuation speeds. The discharge factor is a direct reflection of the signal attenuation speed. In order to establish a more intuitive connection between the material resistivity and material discharge factor, the resistivity of the metal electrode material and the five measured materials is obtained by referring to the material resistivity handbook, so the contact resistance can be acquired. The average discharge factors are calculated by the measured signals of each material. All results are shown in Table 1. The order of five materials in terms of increasing resistivity is as follows: aluminium, paper, wood, glass and PTFE. It is consistent with the order of calculation results of contact resistance. In addition, according to Eq. 7, the static electricity discharge factor is mainly affected by the resistance to the ground, and contact resistance is the main component of the resistance to the ground. In order to further obtain the relationship between the calculated discharge ratio (discharge factor) and the contact resistance, the average discharge factors of five materials are normalized to the 0-1 ranges. The contact resistance is firstly processed by logarithm transformation and then makes the same normalization as average discharge factors. The results are shown in Fig. 6.

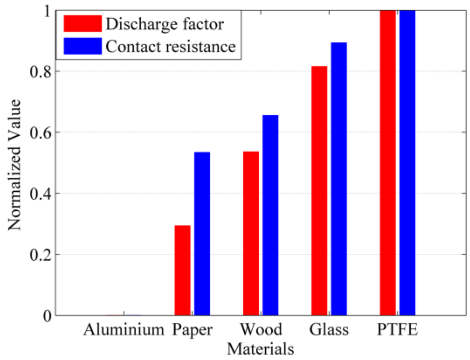

Fig. 6. The relationship between the contact resistances and the average discharge factors

The relationship between resistivity and discharge factor can be obtained through Fig. 6. The results show that the variation trend of the connection between the contact resistivity and the average discharge factor is very similar, which proves the positive correlation among them. Therefore, the contact resistance can be obtained according to the resistivity of the material, so that the resistivity of the material will be identified by using the calculated discharge factor, which is positively related to the contact resistance. Thus by measuring the five kinds of materials electrostatic signals and calculating the corresponding discharge factor which can be used as one of the feature values for materials electrostatic signal identification.

In addition, all the peak values of the electrostatic signals are also quite obvious features. It is a full use of collected data when extracting the positive and negative peak values of the electrostatic signal. Therefore, by adding a time window of 2 seconds to the signal, the positive and negative peaks in the time window will be extracted, and then the variance of positive and negative peaks are obtained. Finally, a two-dimensional vector is extracted from every electrostatic signal as the second feature value. The definition of time window and the positive and negative peaks are shown in Fig. 7.

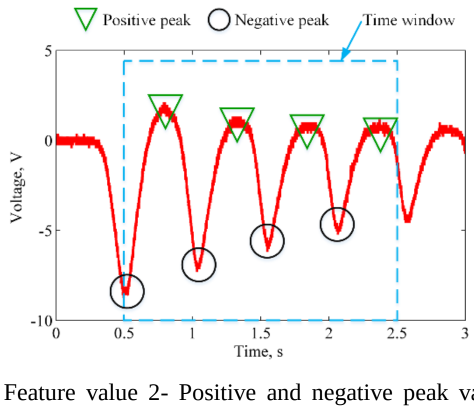

Fig. 7. Feature value 2- Positive and negative peak variance in time window

Table. 1. Resistivity of five kinds of materials, the resistance to ground and the calculated discharge factor

Materials	Aluminium	Paper	Wood	Glass	PTFE
Resistivity, Ω·cm	2.655×10^{-6}	10^{7}	7.362×10^{9}	3.2×10^{15}	10^{18}
Contact resistance	0.934×10^{-6}	4.311×10^{6}	3.173×10^{9}	1.379×10^{15}	4.311×10^{17}
Discharge factor (mean)	0.149	0.390	0.590	0.861	0.966

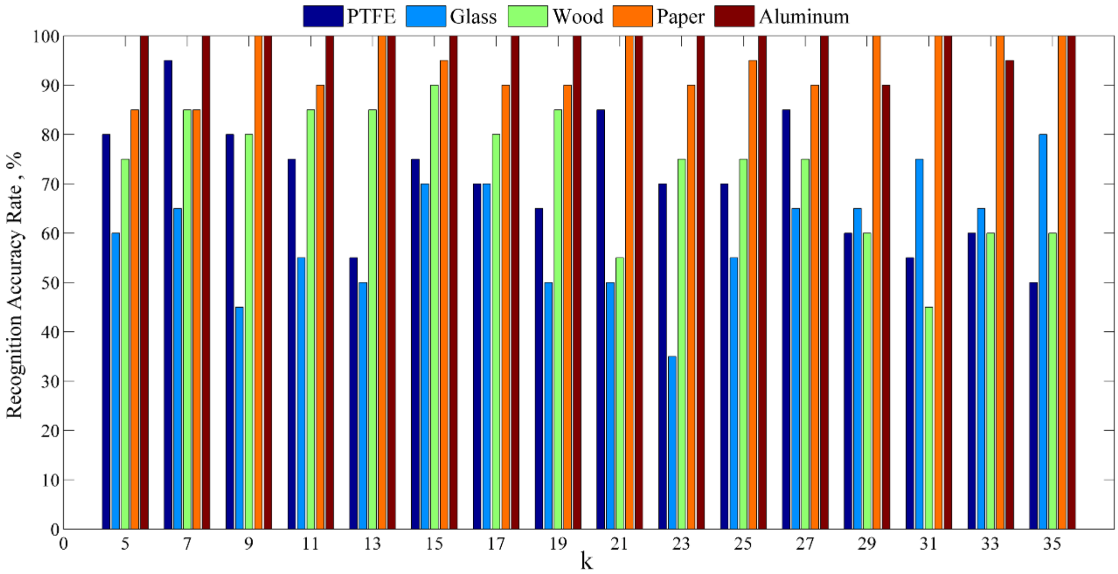

Fig. 8. Recognition accuracy rate of five kinds of materials

Through the extraction and combination of the discharge factor and the variance of positive and negative peaks, the electrostatic signal of each material will be characterized by a three-dimensional feature vector, which is used as the input parameter for the classifier, and the kNN classification algorithm is used to classify the five kinds of materials.

5. RESULTS AND DISCUSSION

After the calculation of two types of feature values of all material electrostatic signals, 50 groups of feature vectors of every material are obtained. Among them, 30 groups of samples are used to train the classifier, and the remaining samples are used to verify the performance of the classifier. The kNN algorithm program is written in MATLAB. After the classifier being trained, the test set is identified and classified. Considering the limited number of samples, it has more advantageous for classification when the k value is odd, therefore the k value is chosen as the odd number between 9 and 35. Finally, the number of correct recognition is obtained, and the recognition accuracy rate is calculated as the following Fig. 8 shows.

As we can see in Fig. 8, the aluminum material can almost be completely correctly and identified with the average recognition accuracy rate of 97.1 %. Paper material also reaches an average of 91.8% higher recognition accuracy rate. Besides, comparing with aluminum and paper, the recognition accuracy rate of glass and PTFE are relatively low as it is 57 % when identifying glass and 65 % identifying PTFE. It is because that the resistivity of glass and PTFE are too close to distinguish efficiently in this method which based on their resistivity. The overall results show that the average recognition accuracy rate of the five materials is 83 % when the k value is 15. In conclusion, even though the method cannot distinguish the material with similar resistivity effectively at present, it is a feasible method based on the material electrostatic signals to classify and identify different materials with significant resistivity.

6. CONCLUSIONS

In this paper, the induced charge model in contact separation process between a metal electrode and charged material is established. The cause of attenuation of the electrostatic signal is analyzed by the discharge model, and the relationship between the resistivity of the measured material and the contact resistance between material and electrode are established. What's more, by designing and establishing a special electrostatic signal acquisition system, the electrostatic signals of five typical materials, aluminum, glass, paper, wood and PTFE, are collected. Based on the calculation of the discharge factor and the positive and negative peak variance in the time window, feature vectors which can represent the electrostatic signals are obtained. Five typical materials electrostatic signal are identified and classified by using the kNN algorithm, and finally, the correct recognition rate of 83 % is achieved.

This method is not affected by the amount of surface charge, and has a good identification effect among those materials which have large resistivity differences. Subsequent researches will further study the direct relationship between the discharge factor and the electrostatic signal, and improve the recognition effect of the materials with similar resistivity.

Acknowledgments

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