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Optimization of key factors of the electrostatic separation for crushed PCB wastes using roll-type separator

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Abstract

For the electrostatic separation process, the separator is most crucial. As a classical one, the roll-type corona-electrostatic separator has some advantages in recycle of waste electrical and electronic equipment (WEEE). Some researches have been done in this field and shown that there was a complex correlation between its configuration and the efficiency of the separation. In this paper, a fractional factorial design (2_{v}^{1-5}) was built and 32 tests were performed on a roll-type corona-electrostatic separator. The sample of granular mixture got from crushed PCB wastes (size 0.3–0.45 mm, containing 25% metal and 75% nonmetal). The experimental data were discussed and used to analyze the factors' main effect, interaction and optimization of the process. Three liner-interaction mathematical models were derived to describe the mass of middling fraction (*M*), conductor fraction (*C*) and Nonconductor fraction (NC), respectively. The results show that the efficiency of the PCB waste electrostatic separation process has a significant correlation with not only factors' main effects, but also the interaction between them.
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Keywords: Waste printed circuit boards; Roll-type corona-electrostatic separator; Fractional factorial design

1. Introduction

Electrostatic separation, defined as the selective sorting of charged or polarized bodies in an electric field [1,2], presents an effective way for recycling metals and plastics from waste electrical and electronic equipment (WEEE) [3]. Some kinds of electrostatic separators have been utilized in laboratory experiments or industry application [4–7]. As a classical one, the roll-type corona-electrostatic separator has some advantages in this field. In general, this kind of separator has several electrodes (Fig. 1): a grounded rotating roll electrode and other active electrodes (corona-electrostatic) connected to a DC high-voltage supply. The granular mixture to be separated is fed on the surface of the rotating roll at a certain speed and pass through the electric field that generated between the roll electrode and active electrodes. After an intense "ion bombardment", nonconductive particles are charged and pinned to the surface of the rotating roll electrode by the electric image force while the conductive ones are charged by electrostatic induction and attracted towards the electrostatic electrode [8].

The electrostatic separation process is influenced by many factors, such as: separator configuration, high-voltage level, material characteristics, feed rate, granule size, ambient condition and the separator is most crucial [9–13]. Some researches have been done in this field and shown that there was a complex correlation between its configuration and the efficiency of the separation [12–15]. As a classical one, the roll-type separator can be effectively used in different situation to recycle metals and plastics form WEEE by optimizing its parameters. However, there are still some problems to be solved. First, the samples of granular mixture that used in previous researches were restricted to chopped electrical wire wastes or mineral and their size were always greater than 1.0 mm. Nevertheless, for chopped PCB wastes, a perfect dissociation of the metals and the insulating matter can only be got when its size is less than 0.6 mm. There is a considerable difference between these two kinds of granular mixture for the electrostatic separation [16,17]. Second, some mathematical models that used to describe the relationship between the separator configuration and the separation efficiency have been derived in previous

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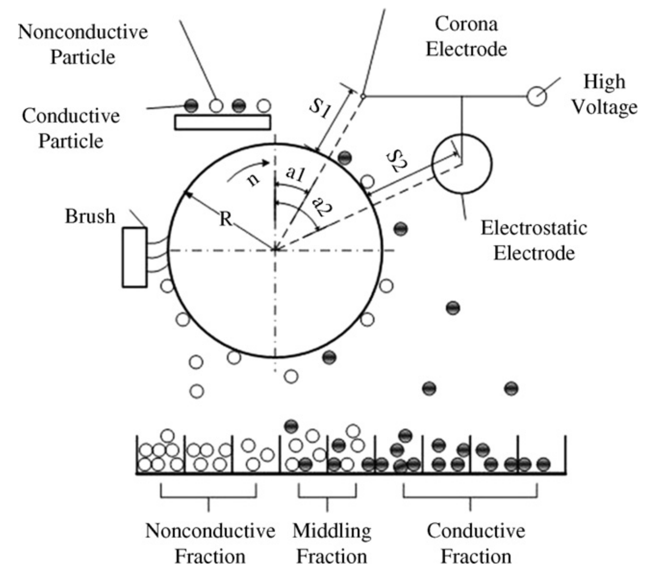

Fig. 1. Key factors of the electrostatic separation process for crushed PCB wastes using roll-type separator.

researches. Unfortunately, some very important interactions were ignored because of the limitation of the experiment-design [12,13].

The aim of this paper is to overcome the above-mentioned problems, analyze the factors' interaction and optimize the process. A fractional factorial design ($2_{\rm v}^{1-5}$) was built and 32 tests were performed on a "roll-type corona-electrostatic separator". Three liner-interaction mathematical models were derived to describe the mass of middling fraction (*M*), conductor fraction (*C*) and nonconductor fraction (NC), respectively.

2. Experimental design

The experimental design is defined as a technique of planning and organizing the experiments based on the statistical principles [18]. The appropriate use of experimental design ensures that experiments can be designed economically and efficiently, and that individual and interaction effects can be evaluated. At the same time, the application of computer program brings about a significant progress in the processing of the experimental data. All of these have proved to be an effective tool for the research of the electrostatic separation process. The first step of the experimental design is to identify the responses, factors and factors' domain of variation for the target. The responses of this research are mass of *C*, *M* and NC. The factors of the electrostatic separation are shown in the following list. In this paper, the parameters U, n, a_1, s_1 and a_2 were considered as notable factors for the process

- U (kV), high voltage level;
- n (min^{-1}), roll speed;
- a_1 (°) and s_1 (mm), position of the corona electrode;
- a_2 (°) and s_2 (mm), position of the electrostatic electrode

and their individual effect and interactions were investigated. The parameter s_2 is a minor factor and assigned a fixed value. Some preliminary experiments are necessary for identifying the domain of variation of these factors and the classical "one-factor-at-a-time" experiments proved to be an effective way for it. Fortunately, these preliminary experiments and a comprehensive discussion have been performed in previous researches and the results are shown in the following list [19].

- U 25–30 (kV);
- n 60 −80 (min^{-1});
- a_1 25–35 (°) s_1 60–70 (mm);
- a_2 65-75 (°) $s_2 = 90$ (mm)

For the present experiment design, the lower level was assigned "−1" and the higher one was assigned "+1".

The second step is to choose an appropriate design for experiments. For the present research containing many factors (five factors at 2-level), Taguchi design and Fractional Factorial design are feasible. Compared with the classical methods, the Taguchi design leads to a significantly lower number of runs. This is very exciting and has some advantages in many practical processes. However, Taguchi design has an obvious limitation in experimental analysis where some important interactions actually exist. In fact, Taguchi design has a lower resolution compared with the classical one and confounds some interactions that might have notable effects to the process. On the contrary, the Fractional Factorial design needs more number of runs and seems uneconomical and time-consuming. Nevertheless, its higher resolution can provide a more precise result for analysis of interactions. Since one aim of this paper is to investigate the important interactions of the electrostatic separation process, the latter is a better choice. In order to contain five factors at 2-level and avoid the confounding between quadratic interactions, a Fractional Factorial design ($2_{\rm v}^{1-5}$) was arranged and 32 tests (one replication for each test) were performed (Table 1).

3. Method

A laboratorial "roll-type corona-electrostatic separator" was employed for the research of the granular mixture separation (Fig. 2). It has a grounded rotating roll electrode and two active electrodes (corona-electrostatic) connected to a DC high-voltage supply (DHV-50 kV/20 mA; 50 kV, peak value and 20 mA, average value). The separator is provided with an electromagnetic vibratory feeder so that ensure a monolayer of granular material on the surface of the rotating roll electrode. The products of the electrostatic separation are recovered in several collecting boxes: No.1–5 boxes were used for collecting the nonconductive fraction, No.6–10 boxes for the middling fraction and No.11–18 boxes for the conductive fraction. The material in each box was weighted, respectively, by an electronic balance with resolution 0.1 g. The sample of granular material is synthetic, got from crushed PCB wastes with size 0.3–0.45 mm. Each sample of test (Fig. 3) was 200 g and contained 25% metals (copper) and 75% nonmetal (woven glass reinforced resin). All experiments were carried out in ambient air, at a temperature of 25 °C and a relative humidity of 55–70%.

Table 1
Factional Factorial design (2_{V}^{1-5}) and 32 tests

Tests	U	n	a_1	s_1	a_2
1	−1	−1	−1	−1	+1
2	+1	−1	−1	−1	−1
3	−1	+1	−1	−1	−1
4	+1	+1	−1	−1	+1
5	−1	−1	+1	−1	−1
6	+1	−1	+1	−1	+1
7	−1	+1	+1	−1	+1
8	+1	+1	+1	−1	−1
9	−1	−1	−1	+1	−1
10	+1	−1	−1	+1	+1
11	−1	+1	−1	+1	+1
12	+1	+1	−1	+1	−1
13	−1	−1	+1	+1	+1
14	+1	−1	+1	+1	−1
15	−1	+1	+1	+1	−1
16	+1	+1	+1	+1	+1
17	−1	−1	−1	−1	+1
18	+1	−1	−1	−1	−1
19	−1	+1	−1	−1	−1
20	+1	+1	−1	−1	+1
21	−1	−1	+1	−1	−1
22	+1	−1	+1	−1	+1
23	−1	+1	+1	−1	+1
24	+1	+1	+1	−1	−1
25	−1	−1	−1	+1	−1
26	+1	−1	−1	+1	+1
27	−1	+1	−1	+1	+1
28	+1	+1	−1	+1	−1
29	−1	−1	+1	+1	+1
30	+1	−1	+1	+1	−1
31	−1	+1	+1	+1	−1
32	+1	+1	+1	+1	+1

Fig. 2. Laboratorial roll-type corona-electrostatic separator.

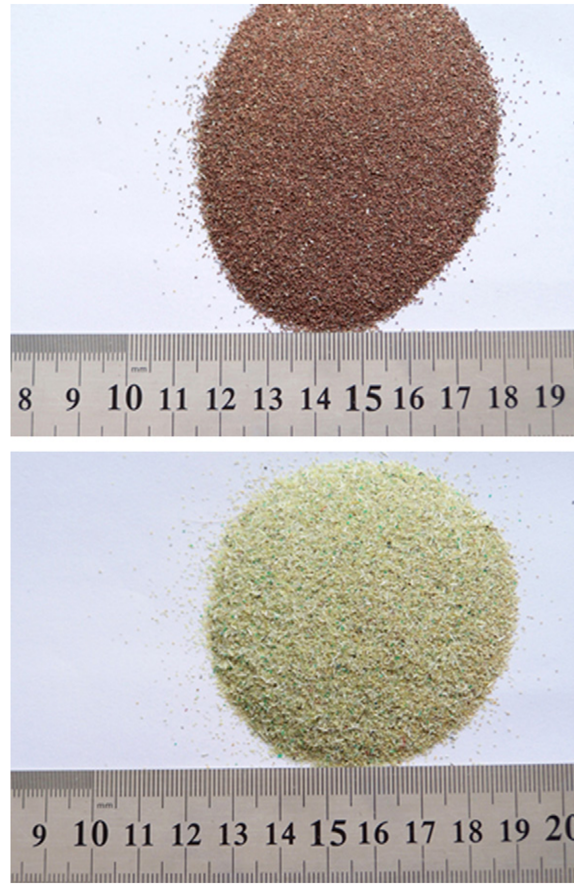

Fig. 3. Sample of granular material (crushed PCB wastes, 0.3–0.45 mm), a is copper and b is woven glass reinforced resin.

4. Results

The results of 32 tests are shown in Table 2. All of these were analyzed by Minitab 15.0 (Minitab Inc., USA). It is an excellent statistical tool for DOE (design of experiment). The variance and the regression analysis of the experimental data were processed by it and three liner-interaction mathematical models were built, respectively, for the mass of C, M and NC. All of models contain ONLY factors and interactions have statistic significance.

$$C = 45.99 + 1.0U* + 0.64n* - 0.48a_1* + 0.54a_2* + 0.35U*a_1* - 0.34U*a_2* \quad (1)$$

$$M = 6.35 - 0.43U* + 0.65n* + 1.13a_1* - 1.21a_2* - 0.32U*n* + 0.42a_1*s_1* - 0.36a_1*a_2* \quad (2)$$

$$\mathrm{NC} = 147.65 - 0.57U* - 1.29n* - 0.65a_1* + 0.28s_1* + 0.67a_2* + 0.36U*n* - 0.39U*a_1* + 0.27U*s_1* - 0.30a_1*s_1* + 0.20a_1*a_2* \quad (3)$$

In the models, the variable U*, n*, a_1*, s_1*and a_2* are the coded units that can only take 1 for the higher level or −1 for the lower one. The main effects plot, interaction plot and cube plot of

Table 2
Results of 32 tests using roll-type separator *C*, mass of conductor fraction (g); *M*, mass of middling fraction (g) and NC, mass of nonconductor fraction (g)

Tests	*C*	*M*	NC
1	45.9	3.8	150.3
2	46.8	6.6	146.6
3	45.5	8.7	145.8
4	48.6	4.6	146.8
5	43.0	7.8	149.2
6	46.4	5.2	148.4
7	46.0	6.4	147.6
8	47.0	9.0	144.0
9	44.2	5.8	150.0
10	46.0	3.4	150.6
11	47.5	5.0	147.5
12	48.0	5.2	146.8
13	44.1	5.8	150.1
14	45.6	8.6	145.8
15	44.0	10.0	146.0
16	47.5	6.3	146.2
17	45.2	4.4	150.4
18	45.9	6.0	148.1
19	46.2	7.0	146.8
20	47.6	5.4	147.0
21	42.0	9.2	148.8
22	47.8	4.6	147.6
23	45.8	7.4	146.8
24	47.9	8.3	143.8
25	44.8	5.0	150.2
26	46.8	2.6	150.6
27	47.2	5.8	147.0
28	47.3	4.3	148.4
29	45.2	4.8	150.0
30	45.8	7.8	146.4
31	43.1	11.8	145.1
32	46.9	6.9	146.2

factors for *C*, *M* and NC are given in Figs. 4 and 5.The optimum factors settings of the mass of *C*, *M* and NC were deduced, respectively, by the models and three duplicate tests were performed for each setting to exam the validity. The results are given in Table 3.

- $U = 30$ kV, $n = 80\,\mathrm{min}^{-1}$, $a_1 = 25°$, $s_1 = 60$ mm, $a_2 = 75°$ and $s_2 = 90$ mm, for maximizing the mass of *C*;

Table 3
Results of duplicate tests for each optimum setting setting 1, maximizing the mass of *C* (g); setting 2 minimizing the mass of *M* (g); setting 3, maximizing the mass of NC (g)

Tests	*C*	*M*	NC
Setting 1	48.8	4.8	146.4
	47.9	5.4	146.7
	48.1	4.9	147.0
Setting 2	46.9	3.3	149.8
	47.1	4.0	148.9
	46.4	3.6	150.0
Setting 3	44.3	5.0	150.7
	45.6	4.4	150.0
	45.2	4.8	150.0

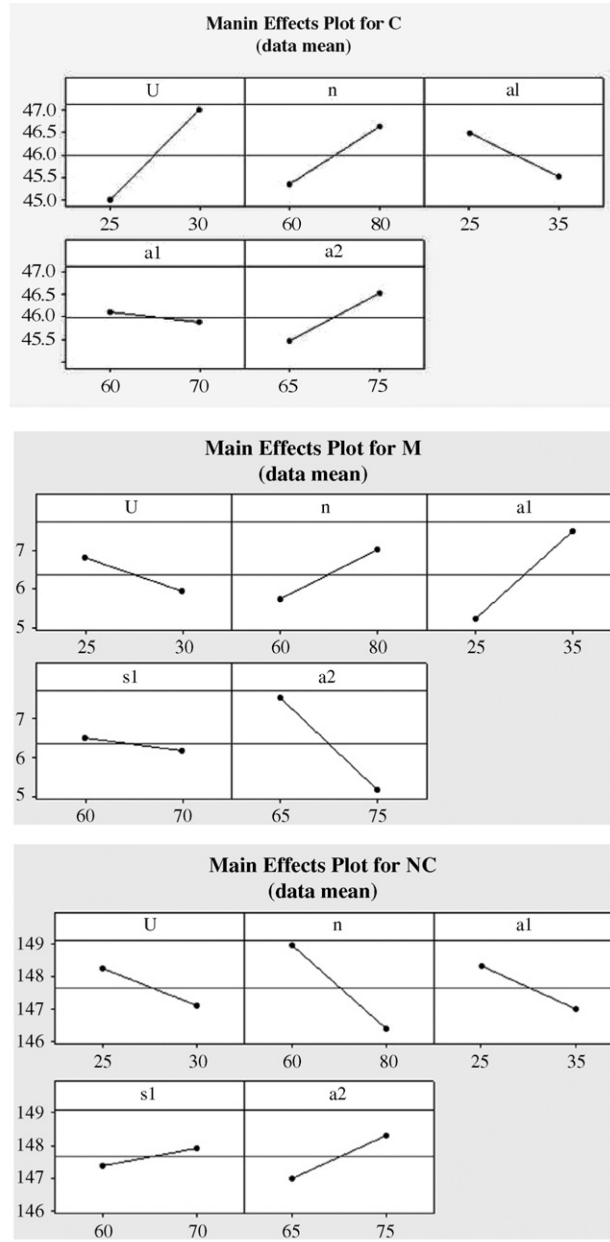

Fig. 4. Main effects of factors for *C*, *M* and NC.

- $U = 30$ kV, $n = 60\,\mathrm{min}^{-1}$, $a_1 = 25°$, $s_1 = 70$ mm, $a_2 = 75°$ and $s_2 = 90$ mm, for minimizing the mass of *M*;
- $U = 25$ kV, $n = 60\,\mathrm{min}^{-1}$, $a_1 = 25°$, $s_1 = 70$ mm, $a_2 = 75°$ and $s_2 = 90$mm, for maximizing the mass of NC.

5. Discussion

The factors' main effects and interactions were analyzed by examining the models 1–3 and Figs. 4–6. For *C*, high voltage level, roll speed, angle position of the corona and electrostatic electrode are the key factors. The mass of conductor fraction increases with a higher voltage level, a higher roll speed and a larger space between corona and electrostatic electrode. It is very clear that the higher voltage level create a stronger electrostatic field and the lager space between two electrodes make the distribution of the field more extensive and uniform. The induction charging of metal is improved. The higher roll speed brings about the stronger centrifugal force and enhances the separation effect of metallic particles. In addition, two interactions: Ua_1, Ua_2 proved to be important. According to the model 1, these two interactions have contrary signs compared with the a_1 and a_2. It means that the output of conductor fraction will be impaired when two electrodes keep a larger space, even if the voltage maintaining a higher level. The phenomena indicate that the direct proportion between the voltage level and the mass of C can reliable ONLY in a finite range.

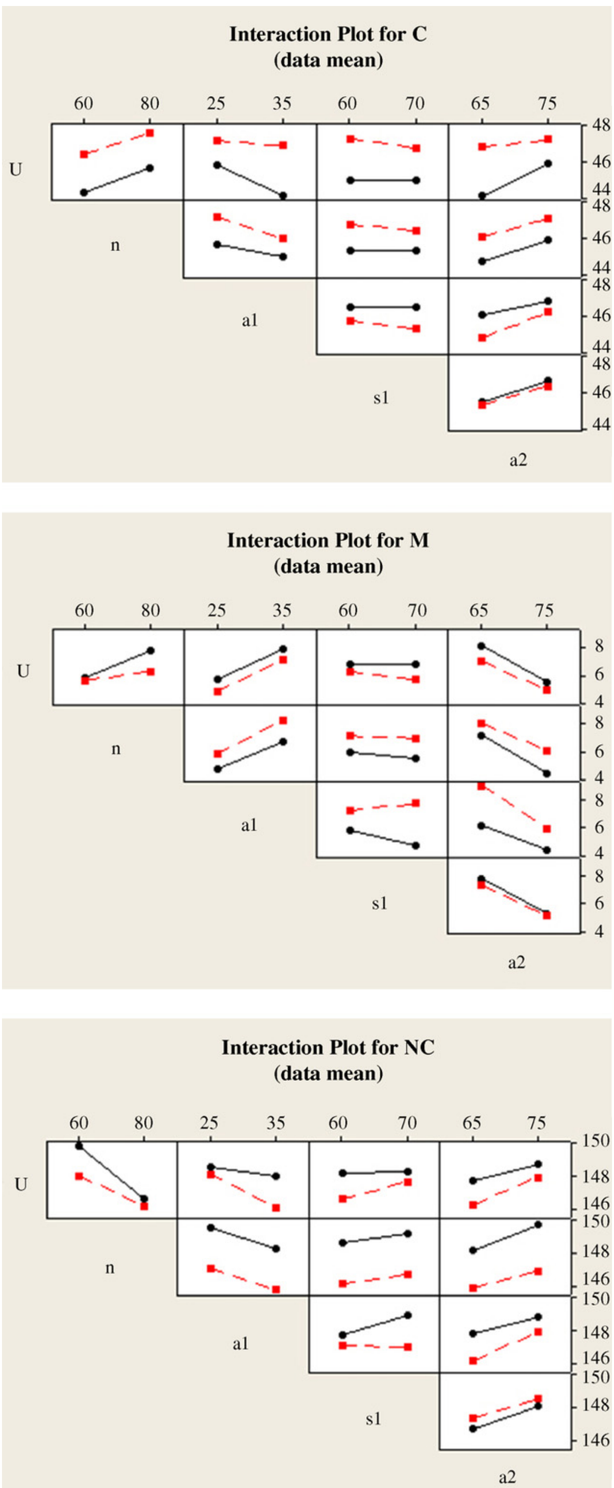

Fig. 5. Interaction of factors for C, M and NC (the unparallel lines represent the interact.

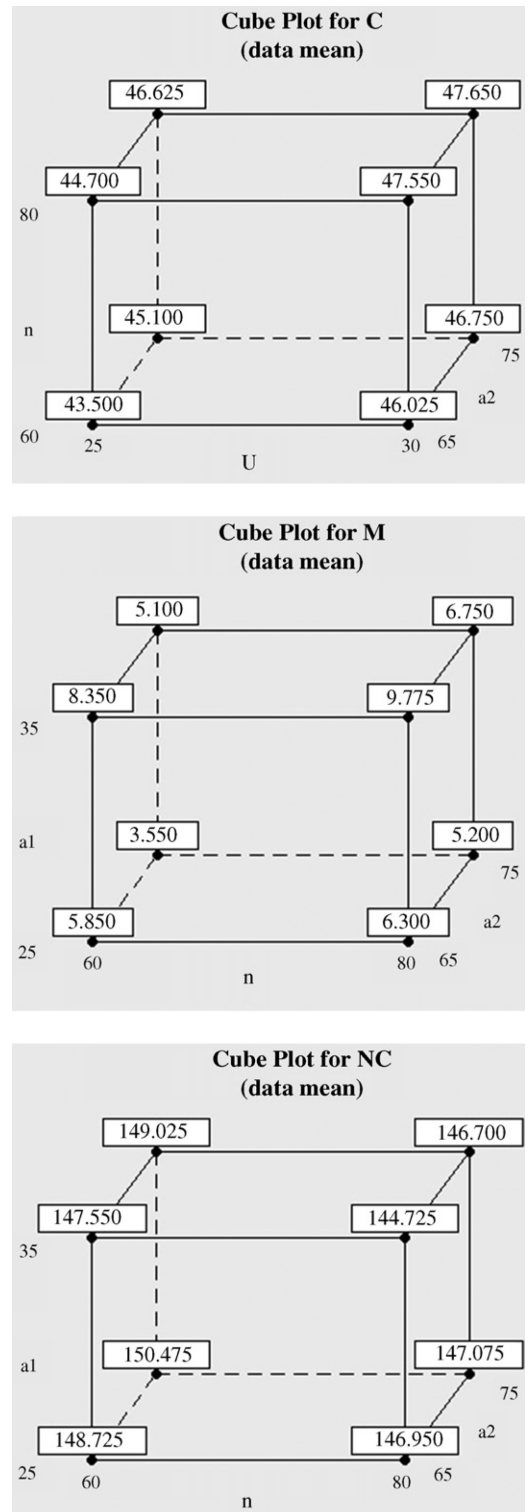

Fig. 6. Cube Plot of factors for C, M and NC.

Compared with the model 1, other three interactions (Un, a_1s_1 and a_1a_2) were examined for M besides the high voltage level, roll speed, angle position of the corona and electrostatic electrode. The mass of middling fraction decreases with a higher voltage level, a lower roll speed and a larger space between corona and electrostatic electrode. The explanation is similar to the foregoing analysis for C. A very good charging condition for nonconductive particle is created by the higher voltage level and the lager space between two electrodes. In addition, the lower roll speed can not only reduce the centrifugal force, but also prolong the retention time of the nonconductor in the ionic zone. Interactions are also important to this process. According to the model 2, there is a bad result for minimization of M when two electrodes are located closely and the interaction a_1a_2 aggravates it simultaneity. This phenomenon can be interpreted by the relative position of two electrodes. The proximity of the electrostatic electrode reduces the local field intensification at the surface of the corona electrode and hence generates a weaker space charge [10]. This is very disadvantageous for charging of nonconductor and its separation. The similar situation is examined for the interaction Un. When U and n are set at a disadvantage level for minimization of M, the result will become worse because of the interaction. Although s_1 is not a key factor for this process, the interaction a_1s_1 has a greater effect than foregoing two interactions according to the coefficient of the model 2. It indicates that the electrostatic field can be improved more extensively by a larger space between the corona electrode and the roll when the angle position a_1 is smaller.

All of five factors are significant for maximizing the mass of NC. The high voltage level, roll speed and angle position of the corona a_1 are in inverse proportion to it and the rest are just contrary. Five interactions were investigated for it. The explanation of the result is same to the C and M.

According to each model, the optimum setting can be confirmed. For maximizing the mass of C, the setting should be $U = 30\,\text{kV}$, $n = 80\,\text{min}^{-1}$, $a_1 = 25°$, $s_1 = 60\,\text{mm}$, $a_2 = 75°$ and $s_2 = 90\,\text{mm}$. This can be examined by the duplicate tests and the average $(48.8 + 47.9 + 48.1)/3 = 48.3\,\text{g}$. This is a good output for the process. The similar results can be concluded for the process of minimizing the mass of M and maximizing the mass of NC. The setting should be $U = 30\,\text{kV}$, $n = 60\,\text{min}^{-1}$, $a_1 = 25°$, $s_1 = 70\,\text{mm}$, $a_2 = 75°$, $s_2 = 90\,\text{mm}$ for the former and $U = 25\,\text{kV}$, $n = 60\,\text{min}^{-1}$, $a_1 = 25°$, $s_1 = 70\,\text{mm}$, $a_2 = 75°$, $s_2 = 90\,\text{mm}$ for the latter. Furthermore, the cube plots that formed by three most important factors are given in Fig. 6 and the clearer results are represented for the optimizing of each process.

6. Conclusion

The DOE (design of experiment) is an effective tool for investigating a multifactor process, as well as for the electrostatic separation for PCB wastes. An appropriate fractional factorial design can be used to analyze factors' main effects, interactions and establish mathematical models. For the present research, some interactions were examined and their effects proved to be significant for the electrostatic separation. Three mathematical models were derived from the experiments for C (the mass of conductor fraction), M (the mass of middling fraction), NC (the mass of nonconductor fraction) and the optimum factors settings were identified, respectively.

The present experiments pave the way for the next research. Firstly, some factors can be eliminated and the more precise models can be built to analyze the nonlinear relation between factors and responses. In this paper, the factor s_1 has proved to be minor to other factors and can be removed. The angle position a_2 has a notable effect for each processes, however, it is very obvious that almost all good results can get when the factor a_2 locates a higher level. So, it can be regarded as a fixed value in the next research too. Secondly, the models and optimum settings can be used to guide the development of a new separator—"two-roll type corona-electrostatic separator". The comprehensive investigation will be presented in the next paper.

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