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A new two-roll electrostatic separator for recycling of metals and nonmetals from waste printed circuit board

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ABSTRACT

The electrostatic separation is an effective method for recycling waste electrical and electronic equipment (WEEE). The efficiency of electrostatic separation processes depends on the ability of the separator. As a classical one, the roll-type corona-electrostatic separator has some advantages in recycling metals and plastics from waste printed circuit board (PCB). However, its industry application still faces some problems, such as: the further disposal of the middling products of the separation process; the balance of the production capacity and the good separation efficiency; the separation of the fine granular mixture and the stability of the separation process. A new "two-roll-type corona-electrostatic separator" was built to overcome the limitation of the classical one. The experimental data were discussed and the results showed that the outcome of the separation process was improved by using the new separator. Compared with the classical machine, the mass of conductive products increases 8.9% (groups 2 and 3) and10.2% (group 4) while the mass of the middling products decreases 45% (groups 2 and 3) and 31.7% (group 4), respectively. The production capacity of the new machine increases, and the stability of the separation process is enhanced.

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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 nonmetals 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: 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 with a certain speed and pass through the electric field that generated between the roll electrode and active electrodes. After an intense "ion bombardment", insulating particles are charged and pinned to the surface of the rotating roll electrode by the electric image force while the conducting ones are charged by electrostatic induction and attracted towards the electrostatic electrode [8].

Some researches have been done in this field and shown that the efficiency of this kind separator is influenced by many factors [9–12], such as: material characteristics, the high-voltage level, the electrode configuration, the feed rate, the granule size, the roll speed and the ambient condition. By adjusting the correlation of these factors, the roll-type separator can be effectively used in different situation to recycle metals and plastics from waste printed circuit board (PCB). However, there are still some problems to be solved. Firstly, the middling products of the process need a further separation for its high content of metals. Secondly, the classical separator cannot give attention to the production capacity and the good separation outcomes simultaneously. For a classical one, a higher production capacity needs a higher feed speed and roll speed. Nevertheless, the higher roll speed brings about more middling products and leads to lower separation efficiency eventually. Thirdly, for crushed PCB wastes, a perfect dissociation of the metals and the nonmetals can only be received when its size is less than 0.6 mm [13,14]. The electrostatic separation of this fine granular mixture is up against the influence of the electrical field wind and the aggregation of granules. Because of this influence, a considerable mass of metals that belong to the conductive products is collected in the nonconductive products. Finally, the stability of the outcome by using the classical separator is not perfect in view of the system errors and some influencing factors.

The aim of this paper is to build a new separator, "two-roll corona-electrostatic separator", to overcome the limitation of the classical one. A series of experiments were carried out in order to

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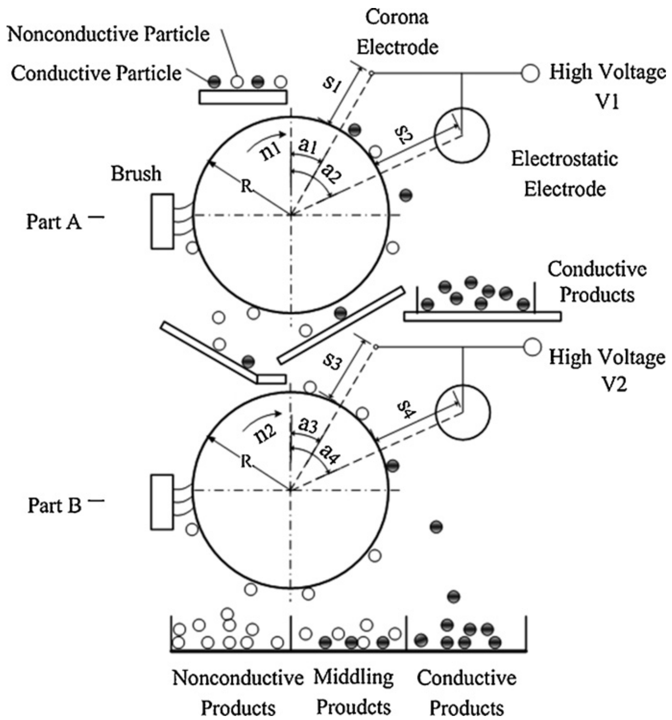

Fig. 1. Schematic representation of the two-roll-type corona-electrostatic separator.

study the key factors that impact the separation process and the peculiarities of this new separator were discussed.

2. Experimental setup

A laboratory “two-roll-type corona-electrostatic separator” (Fig. 1) was employed for the experimental study of granular mixture separation. It consists of two classical roll-type separators (parts A and B) that arrayed in the vertical position. Each one has the same electrode configuration (a grounded roll electrode, a wire-type corona electrode and a cylinder electrostatic electrode). Two chutes were used to collect the middling products and the nonconductive products of the first separation, and send them to the next step as materials of the second separation. An insulating board was used as the shield to prevent the interaction between two electric fields that generated respectively by the electrode-system of parts A and B. Each part is provided with an electromagnetic vibratory feeder and a monolayer of granular material can be formed on the surface of the rotating roll electrode. The products of the electrostatic separation (processes A and B) are recovered in several collecting boxes.

The entire experiment was carried out in four groups and the settings of the factors are given in Table 1. The high-voltage level and the position parameters of the corona electrode and electrostatic electrode are invariable (U = 30 kV, $a_1 = 25^\circ$, s_1 = 70 mm, $a_2 = 75^\circ$ and s_2 = 90 mm). The optimum settings of the factors for the process (minimizing the mass of the middling products) have been investigated in some previous papers [13–15]. For the first group, the separation process was performed on a classical roll-type separator with the same configuration to the part A of the new one. The aim of this group is to build a control experiment and make a comparison between these two separators. The other three groups of the experiment were performed on the two-roll-type separator with different factor settings. For group 2, the settings of part A and B are same to the classical separator used in group 1. It is a simple combination of two parts and equivalent to two separation processes by using the classical separator. Nevertheless, groups 3 and 4 have some notable changes in part A or B. For the former, the higher roll speed and feed rate were introduced in the part A. For the latter, the higher roll speed and feed rate were set not only in part A, but also in part B.

For the two-roll separator, the component of feed is different in two separation processes. There is a lower content of copper (5%) in the second process compared with the first one (25%). Fortunately, the separation efficiency is very little influenced by the copper content of the input [16]. It means that the position parameters of the corona electrode and electrostatic electrode (a_1, s_1, a_2 and s_2) could be invariable, as well as the high-voltage level.

The synthetic metal-insulation granular mixtures (Fig. 2) employed in all experiments were prepared by crushed PCB wastes with size 0.3–0.45 mm. Each sample of test was 200 g and contained 25% metals (copper) and 75% nonmetals (woven glass reinforced resin). Each group of the experiment consists of 10 tests. The

Table 1
Settings of four groups

Group	Part A	Part B
1	$N^a = 60$, $W^b = 20$	Null
2	$N = 60$, $W = 20$	$N = 60$, $W = 20$
3	$N = 120$, $W = 40$	$N = 60$, $W = 20$
4	$N = 120$, $W = 40$	$N = 90$, $W = 30$

[a] N, roll speed (rpm).
[b] W, feed rate (g/min).

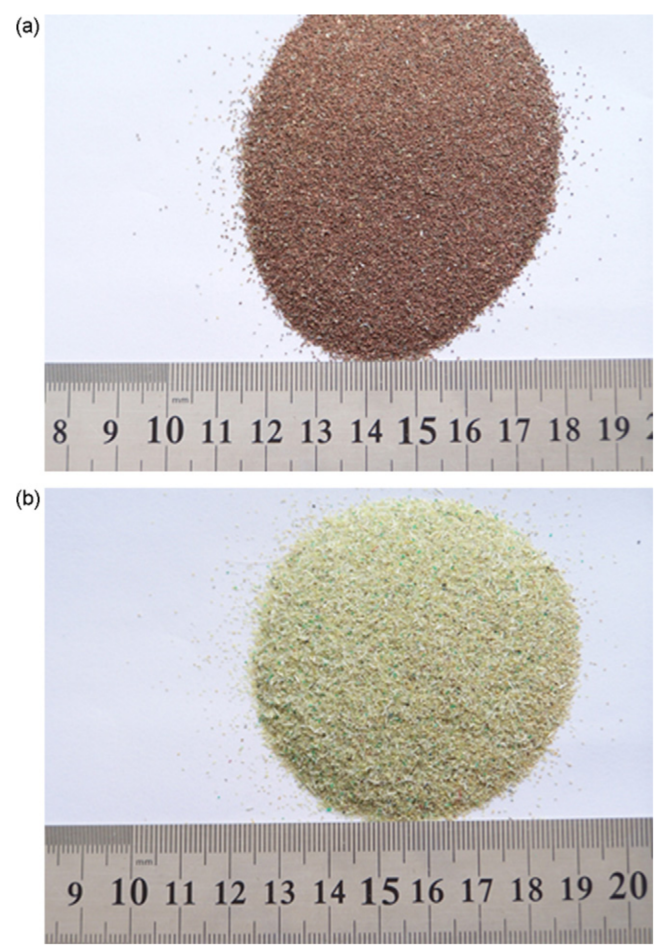

Fig. 2. Sample of granular material (crushed PCB wastes, 0.3–0.45 mm), ‘a’ is copper and ‘b’ is woven glass reinforced resin.

Table 2
Results of the electrostatic separation

Test	Group 1			Group 2			Group 3			Group 4		
	C[a]	*M*[b]	NC[c]	*C*	*M*	NC	*C*	*M*	NC	*C*	*M*	NC
1	44.5	6.0	149.5	49.0	2.8	148.2	48.8	3.0	148.2	49.7	3.7	146.6
2	45.8	5.2	149.0	48.7	3.5	147.8	48.6	3.5	147.9	49.2	4.4	146.4
3	46.9	4.7	148.4	49.0	3.6	147.4	49.1	2.8	148.1	50.3	4.9	144.8
4	44.3	7.0	148.7	49.1	3.1	147.8	48.5	3.5	148.0	49.5	3.7	146.8
5	44.8	6.2	149.0	49.4	3.5	147.1	49.0	3.4	147.6	49.8	4.1	146.1
6	45.0	5.8	149.2	48.8	3.2	148.0	49.3	2.6	148.1	50.1	4.5	145.4
7	44.0	7.3	148.7	49.2	3.4	147.4	49.2	3.3	147.5	49.9	4.2	145.9
8	43.8	6.6	149.6	49.5	2.9	147.6	48.9	4.0	147.1	49.1	3.8	147.1
9	45.6	5.6	148.8	48.9	3.7	147.4	48.9	2.9	148.2	49.8	3.5	146.7
10	46.0	5.5	148.5	49.3	3.0	147.7	49.0	3.4	147.6	49.6	3.9	146.5
Sample mean	45.1	6.0	148.9	49.1	3.3	147.6	49.0	3.2	147.8	49.7	4.1	146.2

[a] *C*, the mass of conductive products (g).
[b] *M*, the mass of middling products (g).
[c] NC, the mass of nonconductive products (g).

product of each test was weighted respectively by an electronic balance with resolution 0.1 g. All experiments were carried out in ambient air, at a temperature of 24 °C and a relative humidity of 50%–60%.

3. Results

The separation results are shown in Table 2. Obviously, the separation processes that performed on the two-roll separator are better than it on the classical one not only in minimizing the mass of middling products (*M*), but also in maximizing the mass of conductive products (*C*). Group 4 obtains the maximal mass of conductive products, 49.7 g (mean). Group 1 gets the maximal mass of nonconductive products (NC), 148.9 g (mean). The outcomes of groups 2 and 3 show some similarities and get the minimal mass of middling products, 3.3 g (mean) for group 2 and 3.2 g (mean) for group 3, respectively.

The statistic analysis of results was performed by SPSS15.0 (SPSS Inc., USA) and shown in Table 3. Table 3(part 1) is an example

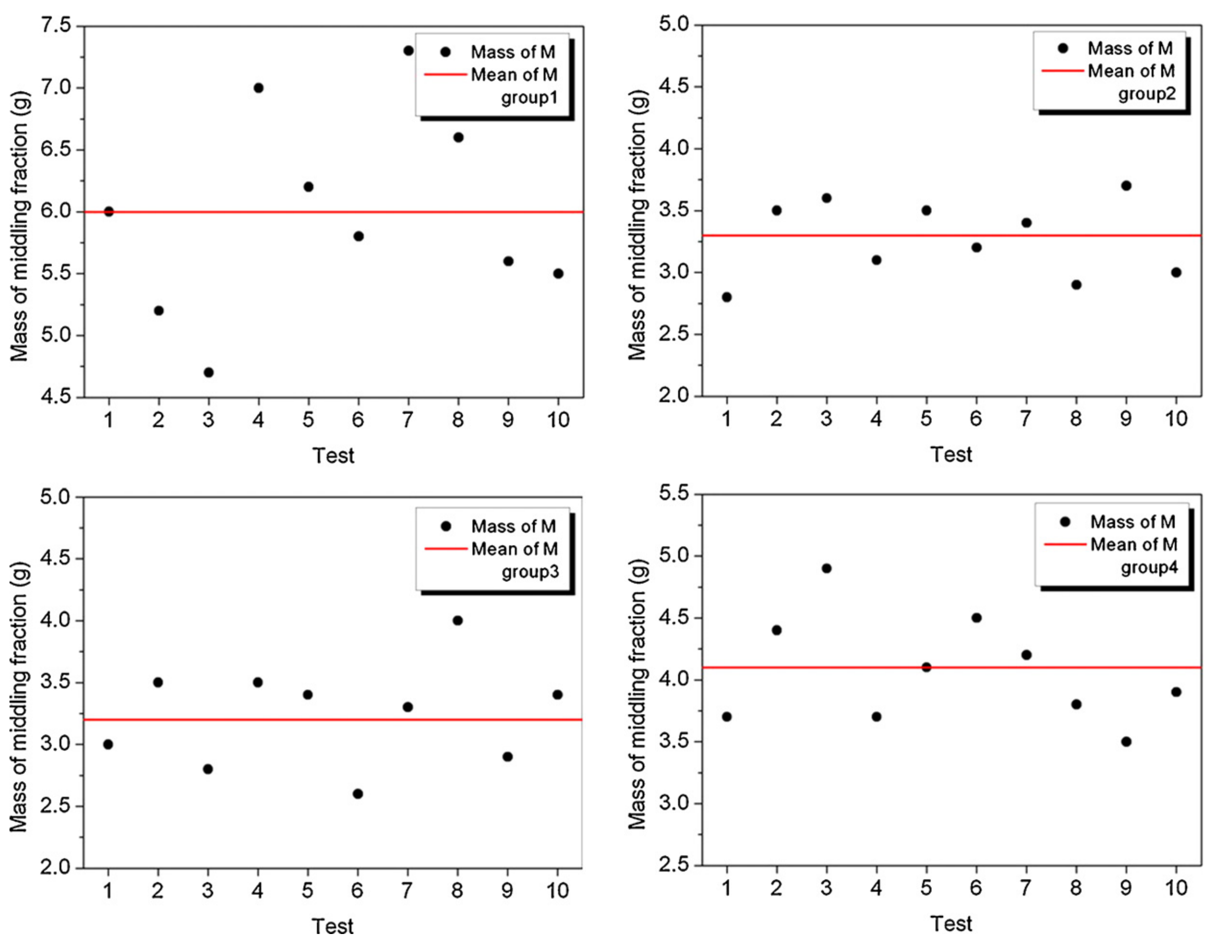

Fig. 3. The stability of separation processes.

Table 3
Independent samples test

	Levene' s test for equality of variances		*t*-test for equality of means						
								95% Confidence interval of the difference	
	F	Significance	*t*	df	Significance 2tailed	Mean difference	Standard error difference	Lower	Upper
Part 1: An example of independent samples test for groups 1and 2 (mass of the middling fraction)									
Equal variances assumed	7.683	.013	8.500	18	.000	2.61000	.30705	1.96492	3.25508
Equal variances not assumed			8.500	11.198	.000	2.61000	.30705	1.93565	3.28435

	C		*M*		NC	
Part 2: Results of independent samples test for four groups						
	1–2 (+)[a]	2–3 (−)[b]	1–2 (+)	2–3 (−)	1–2 (+)	2–3 (−)
	1–3 (+)		1–3 (+)		1–3 (+)	
Groups	1–4 (+)		1–4 (+)		1–4 (+)	
	2–4 (+)		2–4 (+)		2–4 (+)	

[a] (+), means significant difference.
[b] (−), means no significant difference.

Table 4
The processing time (min) of the electrostatic separation

Processing time	Group 1	Group 2	Group 3	Group 4
Part A	10	10	5	5
Part B	Null	7.5	7.5	5
Total	10	10	7.5	5

for "independent samples test"—a tool for judging the difference between two group data. In the present paper, this tool was used to judge the difference between the separation results of groups, and then, to show the difference between the classical machine and the new one.

No matter what aspect of outcomes, *C*, *M* or NC, group 1 always show the significant differences compared with others. However, group 2 and 3 represent the similarity to some extent.The processing time of each experimental group is calculated by the formula (1)

$$D = \frac{S}{W} \quad (1)$$

where *D* is processing time of process; *S* is amount of sample and *W* is feed rate. The results are given in Table 4. For the two-roll separator, parts A and B run simultaneously. So, the processing time of each group should be the maximum among the time of parts A and B.

The stability of separation processes is shown in Fig. 3. Compared with group 1, there is a lower dispersion in groups 2 and 3. For group 4, the discrete degree of data is between fore-mentioned groups.

4. Discussion

Some preliminary information can be got from Table 2. Compared with the outcomes of group 1 (using classical separator), groups 2–4 (using two-roll separator) are better. This phenomenon is easy to explain. There always exists a considerable amount of metals in the middling products of the separation process even under the good conditions. At the same time, another part of metals is collected in the nonconductive products because of the influence of the electrical field wind and the conglomeration of granules. These two reasons induce a decrease of the metals recovery. These problems can be solved by twice, thirce or more separation processes and the two-roll separator just take this idea. The two-step-separation makes a progress in the outcomes, *C* increases 8.9% for groups 2 and 3; and 10.2% for group 4 while *M* decreases 45% for groups 2 and 3; and 31.7% for group 4, respectively. Obviously, two-step separation of the new machine makes a further disposal and extracts more metals from the middling and the nonmetal products, reduces the mass of middling products.

The statistic analysis in Table 3 gives a further proof about the differences between these two kind separators. Table 3(part 1) gives a detailed example of independent samples test for *M* of groups 1 and 2. The results of independent samples test for others are shown in Table 3(part 2). No matter what aspect of outcomes *C*, *M* or NC shows; groups 2–4 always show the significant differences compared with group 1. This indicates that the outcomes of separation using two-roll separator is actually better than the classical one. The similar significant difference exists between groups 2 and 4, however, groups 2 and 3 show the similarity to some extent based on the statistic analysis. The experimental results have showed this phenomenon. The outcomes of *C*, *M* and NC of groups 2 and 3 are all approximate and group 4 is different. For a two-roll separator, this phenomenon is brought about by the parameter setting

Table 5
Descriptive statistics

	N	Range	Minimum	Maximum	Mean	S.D.	Mean square deviation
Group 1	10	2.6	4.7	7.3	5.990	0.8075	0.652
Group 2	10	0.9	2.8	3.7	3.270	0.3129	0.098
Group 3	10	1.4	2.6	4.0	3.240	0.4142	0.172
Group 4	10	1.4	3.5	4.9	4.070	0.4347	0.189

in parts A and B. It can be checked that the same settings in part B (groups 2 and 3) and finally lead to the similar outcomes while the different ones result in diverse outcomes. However, the settings in part A show no inference about it. This implies that the part B is the key part of the quality control (minimizing the mass of middling products) for the two-roll separator. Within the normal range, no matter what parameters are set in part A, the quality of the separation process is eventually depended on the setting in part B.

Besides the quality of the products, the production capacity is also important for the industrial process. For the electrostatic separation of WEEE, the larger production capacity needs a higher feed speed and roll speed. Nevertheless, the higher roll speed brings about more middling products and leads to lower separation efficiency eventually. This is a dilemma for the classical separator but can be improved by the two-roll machine. Because of the second-step separation of the part B, the higher feed speed and roll speed can be set in part A in spite of the increase of the middling products. In the present experiments, the mass of feed is 200 g for part A and 150 g for part B (remove the mass of conductive products). This effect can be informed from Table 4, the processing time of groups 3 and 4 (higher feed speed and roll speed in part A) reduces 25% and 50% respectively compared with groups 1 and 2 (lower feed speed and roll speed in part A). This result means that the two-roll separator can dispose more materiel in a same period of time. However, part A is NOT the only factor that influence the processing time, the higher feed speed and roll speed in part B can make a further decrease of the processing time (group 4). Although this setting brings about more middling products compared with group 3, the result is still better than group 1 that performed on the classical separator. In addition, the higher roll speed is benefit for the recovery of the metals and this is the reason for the maximum metal products of group 4.

Stability is another important index for the industrial process. For the electrostatic separation, the mass of middling products is used as a criterion to estimate the results of the process [17]. The scatter-plot of the mass of middling products is given in Fig. 3. It shows the degree of scatter for the results of experiments. The further evidence of stability is shown in Table 5: the mean square deviation of the "*M*" fraction (calculated by SPSS15.0). These data indicates that the outcome of group 1 (range = 2.6, mean square deviation = 0.652) is more unstable than other three groups. The fluctuation comes from the systematic error and random error. The electrostatic separation is influenced by many controllable factors (the high-voltage level, the electrode configuration, the feed rate, the roll speed) and the uncontrollable factors (the character of material, ambient condition). The multi-separation can improves the situation that influenced by the systematic error and random error and lets the separation process becomes more stable. This is very important for industrial process.

5. Conclusion

The present paper built a new "two-roll separator" to overcome the limitation of the classical one. The results of experiments in four groups indicate that the two-step separation of the new machine can make progress compared with the classical one. Firstly, the mass of conductive products increases 8.9% for groups 2 and 3; and 10.2% for group 4, respectively. At the same time, the middling products decrease 45% for groups 2 and 3; and 31.7% for group 4, respectively. Secondly, the production capacity of the new machine increases 25% for group 3 and 50% for group 4, respectively. Thirdly, the stability of the separation process is enhanced compared with the classical one.

The "two-roll separator" was built based on the theory of electrostatic separation. However, it doesn't mean that the new machine is a simple series connection of two old ones. Firstly, compared with the simple series connection of two "roll-type separators", the configuration of the "two-roll separator" is more compact and efficient. The new machine makes use of the gravity force to convey the granule mixture to the second step. This configuration avoids a transport unit, diminishes the cost and processing time. This is significant for the industrial application. Secondly, for a two-roll separator, parts A and B take charge with different functions respectively. The part B is a key part of the quality control (minimizing the mass of middling products) for the two-roll separator. The part A (associated part B) is a control factor for the production capacity. Compared with the simple two-step separation, these characteristics enable the two-roll separator to treat the crushed WEEE more effectively and flexibly.

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