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# A model for simulating the grinding and classification cyclic system of waste PCBs recycling production line

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ABSTRACT

Crushing and separating technology is widely used in waste printed circuit boards (PCBs) recycling process. A set of automatic line without negative impact to environment for recycling waste PCBs was applied in industry scale. Crushed waste PCBs particles grinding and classification cyclic system is the most important part of the automatic production line, and it decides the efficiency of the whole production line. In this paper, a model for computing the process of the system was established, and matrix analysis method was adopted. The result showed that good agreement can be achieved between the simulation model and the actual production line, and the system is anti-jamming. This model possibly provides a basis for the automatic process control of waste PCBs production line. With this model, many engineering problems can be reduced, such as metals and nonmetals insufficient dissociation, particles over-pulverizing, incomplete comminuting, material plugging and equipment fever.



## 1. Introduction

Waste printed circuit boards (PCBs) are recognized as an important part of waste electronic products [1]. PCBs have high recovery value which contain a lot of valuable materials, such as copper, aluminum, iron, nickel, lead and tin, zinc, gold, silver, palladium, rhodium and other precious metals [2,3]. Therefore, the recycle and disposal of waste PCBs have momentous significance from the perspective of resources and environment. Chemical and mechanical methods are two traditional recycling processes for waste PCBs. However, the prospect of chemical methods will be limited since the secondary pollution brought by the emission of toxic liquid or gas to the environment during the process. Mechanical processes, such as shape separation, jigging, density-based separation, and electrostatic separation have been widely utilized in the recycling industry.

Xu et al. [4–6] developed a set of automatic line without negative impact to environment for recycling waste PCBs in industry-scale. The whole technology contains four parts: multiple scarping, material screening, multiple-roll corona electrostatic separator, and dust precipitation (Fig. 1). In comparison with other production line, the production efficiency and copper recovery rate are higher. Although many problems in the industrialization of technology were solved, there are still some problems blocking the integration of different technologies. If the grinding and classification cyclic system is not well controlled, the whole process will face problems such as metals and nonmetals insufficient dissociation, particles over-pulverizing, incomplete comminuting, material plugging and equipment fever.

In order to make PCBs particle size meet the requirements, the hammer grinder-2, cyclone-1 and vibrating screen constitutes closed-circuit circulation in grinding and classification section as depicted in dashed frame (Fig. 1). Closed-circuit grinding has two main purposes: one is making crushed PCBs reach given size requirement, the other is reducing crushing energy consumption and reducing over-crushed rate which has a significant impact on corona electrostatic separation (CES) [7–9]. Because the process of grinding and classification is complex, and the realization of actual experiment is difficult, we tried to establish a mathematical model to analyze the process. With mathematical model and simulation calculation method, the experimental work can be reduced in the research and optimization of grinding circuit.

## 2. Cyclic system structure and theoretical aspects

In order to calculate material balance of waste PCBs grinding and classification system, grinding and classification cyclic system (Fig. 2) for modeling and processing is constructed. Each cycle is hypothesized to be finished in a unit of time, and the feeding material weight remains stable in each cycle, so the system chang-

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**Nomenclature**

| | |
|---|---|
| $Q_0, f_0$ | particle flow and particle size distribution of grinder new feeding |
| $Q_1, f_1, p_1$ | material flow through the grinder, particle size distribution before and after the grinder |
| $Q_2, p_2$ | discharging particle flow and size distribution of the cyclone separator |
| $Q_3, p_3$ | feeding particles flow and particle size distribution of vibrating screen |
| $Q_4, p_4$ | product particle flow and particle size distribution of vibrating screen |
| $Q_r, p_r$ | backflow particle flow and size distribution |
| $M$ | the grinding matrix which represents grinder working condition |
| $C_1$ | the classification matrix which represents cyclone working condition |
| $C_2$ | the classification matrix which represent vibrating screen working condition |

ing with time effect can be reflected through cycle times. Other parameters such as cyclone separation classification matrix and vibrating screen classification matrix are assumed to be not change over time, because the model is established in a steady condition, which means the working state of all equipments in the system are assumed to be stable.

### 2.1. Hammer grinder and operation model

The hammer grinder mentioned here is the last step of multiple scraping part. The purpose of comminution is to make metal and nonmetal contained in waste PCBs completely disintegrated, and a certain range of particle size is pulverized. So the follow-up processing will have good efficient in separating disintegrated metal and nonmetal. Pioneer researchers did several studies, which have demonstrated that the PCBs material is completely disintegrated only when the particle size is below 0.6 mm [7].

The hammer grinder mathematical model is used to describe quantitative relationship between feeding and discharging materials (Fig. 3). The material is divided into $n$ grades according to the particle size, so the size distribution of hammer grinder feeding and discharging material can be expressed as an $n \times 1$ column matrix:

$$f_1 = (f_1 f_2 \cdots f_n)^{\mathrm{T}} \quad p_1 = (p_1 p_2 \cdots p_n)^{\mathrm{T}}$$

$$M = \begin{bmatrix} m_{11} & 0 & \cdots & 0 \\ m_{21} & m_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{bmatrix}$$

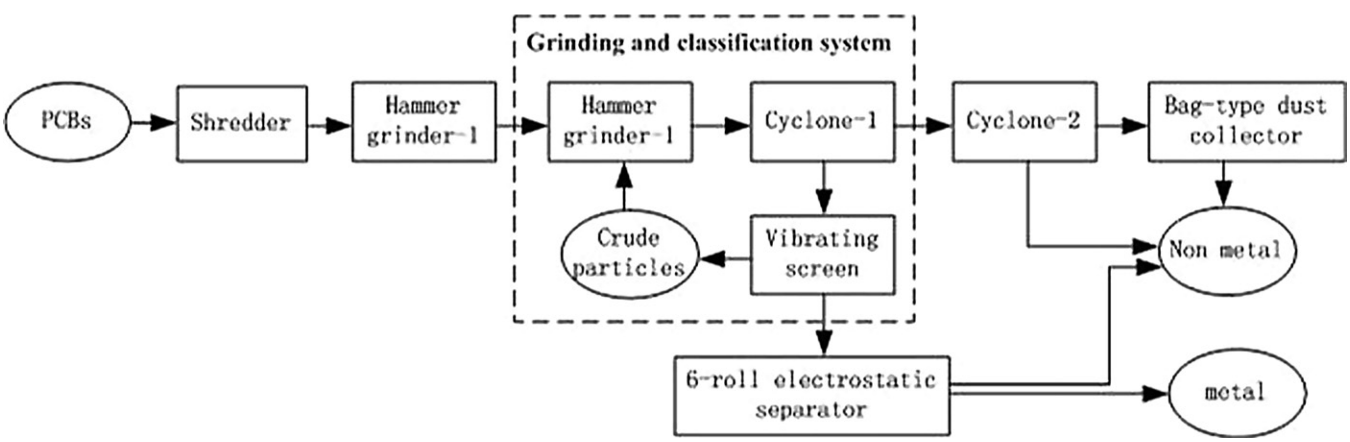


**Fig. 1.** Flow process chart of whole automatic line for recycling waste PCBs.

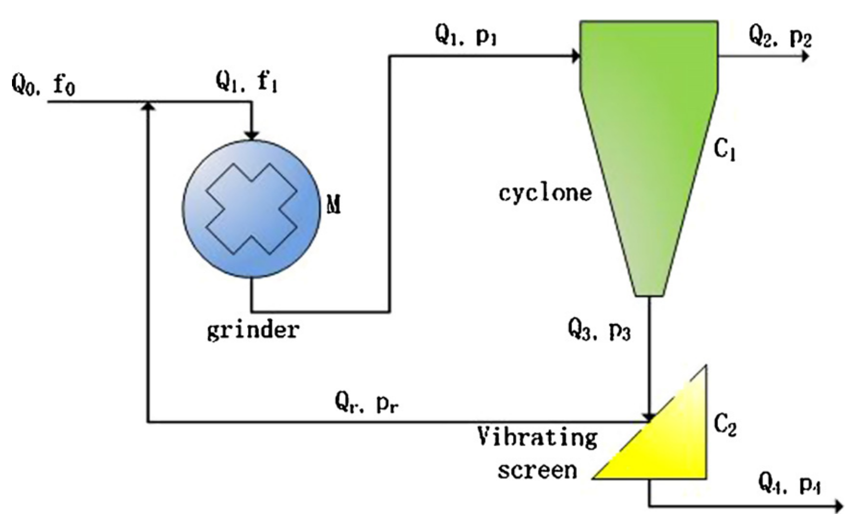


**Fig. 2.** Material flow model of grinding and classification cyclic system.

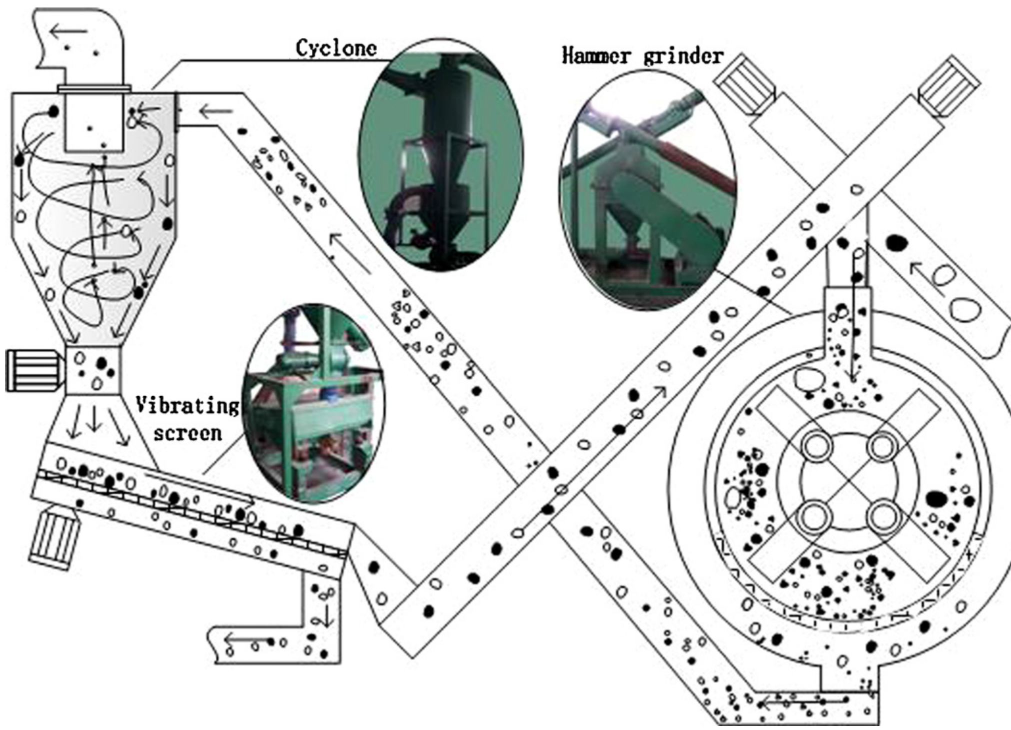


**Fig. 3.** Schematic of grinding and classification cyclic system and the equipment photos.

Here a lower triangular matrix $M$ is used to represent crushing process of each grade particles in the hammer grinder (Fig. 2). The crushing matrix element $m_{ij}$ represents the mass fraction of grade $j$ material becomes grade $i$ material through the effection of hammer grinder. The hammer grinder operation model can be expressed as:

$$P_1 = Mf_1 \tag{1}$$

According to previous research, it is very complicated to investigate the influence factors of crushing matrix $M$ [10–12]. The matrix $M$ mainly depends on grinder performance, grinding time and feeding material composition. In our simulation, crushing matrix $M$ was calculated out according to the hammer grinder feeding and discharging particle size distribution of the practical production line. Under the premise of material balance in this simulation, the matrix $M$ was nearly kept unchanged.

### 2.2. Cyclone separation and operation model

After hammer grinding, waste PCBs particles contain a lot of nonmetal particles which brought negative impact on the electrostatic separation [8]. So a cyclone separation process is applied to separate out as many of the nonmetal particles (Fig. 3). The continuous particles are delivered to cyclone by high speed air (the blast volume of air is appropriately 3000 Pa) [4]. In the airflow movement process, the material flow along the tangential direction to generate circular motion in the cyclone. Because of centrifugal force, metal particles will crash to the wall, slide downward along the wall and finally collected. In the meantime, fine nonmetal particles move together with air flow and then come into the next cyclone.

Cyclone separation process can be expressed with matrix equation. $n \times n$ diagonal matrix is used to express classification matrix, as below:

$$C_1 = \begin{bmatrix} c_1 & 0 & \cdots & 0 \\ 0 & c_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & c_n \end{bmatrix}$$

The diagonal element $c_i$ represents mass fraction of grade $i$ material, which can collected from cyclone separation. Based on the hypothesis that particles have no collision comminution in the process, cyclone separation material balance model can be expressed as follows (Fig. 2):

$$Q_3 p_3 = C_1 Q_1 p_1 \tag{2}$$

The classification matrix mainly depends on material composition, material quantity and air pressure. In our model, interaction of different particle grades material was ignored and $C_1$ was considered as a constant.

### 2.3. Vibrating screening and operation model

After cyclone separation, the collected crude particles are delivered to the vibrating screen. Here a vibration motor is used as vibration source, which can make the material thrown up on the screen (Fig. 3). The vibrating screen mesh is made by wire netting, and the blinding chance from irregular shape of particulate system is reduced to minimum. The size of the screen holes in the vibrating screen is 1.2 mm × 1.2 mm. The screen overflow crude particles are delivered back to hammer grinder by screw conveyor. Then the screen underflow fine particles are fed to 6-roll electrostatic separator for recovering metal and nonmetal particles [4].

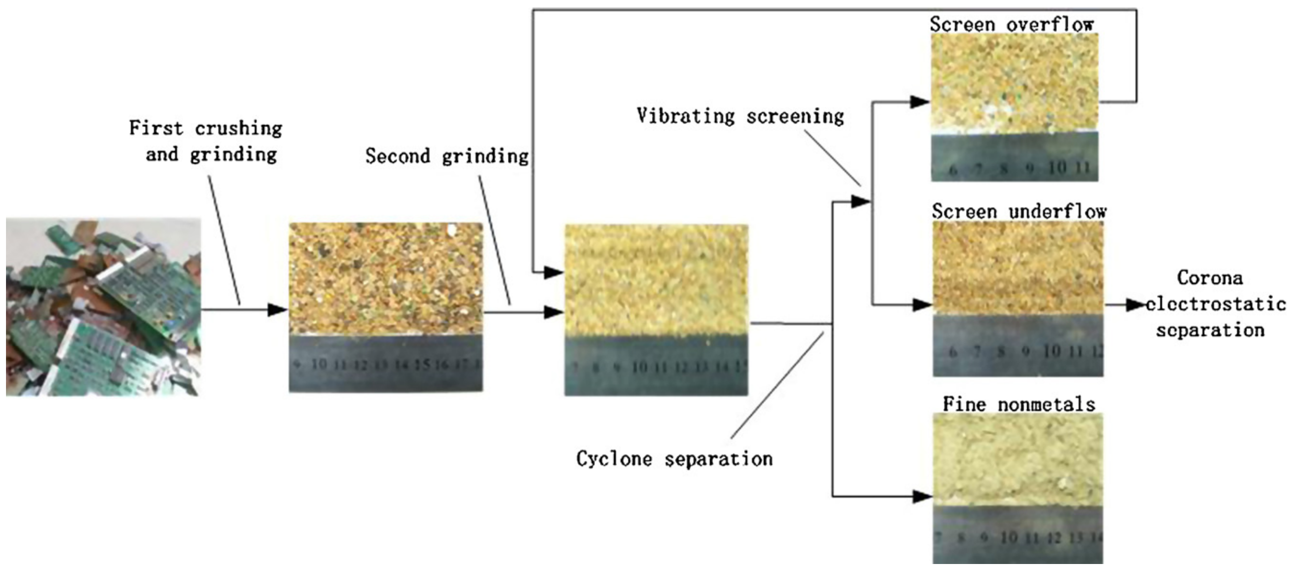


**Fig. 4.** Material graphs in grinding and classification cyclic system.

Vibrating screening process can be expressed with matrix equation (Fig. 2). An $n \times n$ diagonal matrix is used to express classification matrix, as below:

$$C_2 = \begin{bmatrix} c_1 & 0 & \cdots & 0 \\ 0 & c_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & c_n \end{bmatrix}$$

The diagonal element $c_i$ represents mass fraction of grade $i$ material which can be collected into screen overflow particles. Based on the hypothesis the particles have no collision comminution, vibrating screening process material balance model can be expressed as follows:

$$Q_r p_r = C_2 Q_3 p_3 \quad (3)$$

The classification matrix mainly depends on particle property, screen net aperture and vibrating frequency. In our model, interaction of different particle grade material was ignored and $C_2$ was considered as a constant.

### 2.4. Material balance equation

According to the material balance principle, the balance equations as blow were established to reflect particle flow and size distribution in the system [13]:

$$Q_0 f_0 + Q_r p_r = Q_1 f_1 \quad (4)$$

$$Q_1 p_1 = Q_2 p_2 + Q_3 p_3 \quad (5)$$

$$Q_3 p_3 = Q_r p_r + Q_4 p_4 \quad (6)$$

According to the balance relationship of total particle flow in the system, we got the following three equations:

$$Q_0 + Q_r = Q_1 \quad (7)$$

$$Q_2 + Q_3 = Q_1 \quad (8)$$

$$Q_r + Q_4 = Q_3 \quad (9)$$

### 2.5. Calculation formula in stability condition [14,15]

In an ideal state, the entire cyclic system is in a stable condition if the PCBs particles flow and size distribution ($Q_0$, $f_0$) from the primary grinder keep stable, and the working parameters of crusher, air separator, and vibrating ($M$, $C_1$, $C_2$) are constant. When the system operates, the backflow particle flow ($Q_r$) increases at the beginning and finally achieves a stable state. In the production practice, if the return particles flow ($Q_r$) keeps stable and the particle feeding flow ($Q_0$) equals with the particle product flow ($Q_2 + Q_4$), we can make the conclusion that the circuit system have achieved stable state. From formulae (1)–(9), we can deduce the flowing:

$$P_1 = \frac{1}{Q_1}(I - MC_2C_1)^{-1} MQ_0 f_0 \quad (10)$$

$$P_3 = \frac{1}{Q_3} C_1 (I - MC_2C_1)^{-1} MQ_0 f_0 \quad (11)$$

$$P_2 = \frac{1}{Q_2}(I - C_1)(I - MC_2C_1)^{-1} MQ_0 f_0 \quad (12)$$

$$P_4 = \frac{1}{Q_4}(I - C_2) C_1 (I - MC_2C_1)^{-1} MQ_0 f_0 \quad (13)$$

$$P_r = \frac{1}{Q_r} C_2 C_1 (I - MC_2C_1)^{-1} MQ_0 f_0 \quad (14)$$

$$f_1 = \frac{1}{Q_1}[Q_0 f_0 + C_2 C_1 (I - MC_2C_1)^{-1} MQ_0 f_0] \quad (15)$$

### 2.6. Static balance point computation

In order to model the material grinding and classification process it is assumed that:

(1) The feeding weight of waste PCBs particles and size distribution keep unchanged in the system, and the weight is no more than the processing load of hammer grinder, cyclone and vibrating screen.
(2) In each cycle, the air separator and vibrating screen classification matrix remain unchanged, and the grinding matrix $M$ basically remain stable in consideration of keeping the grinder feeding and discharging material balanced.

The MATLAB software is used for programming, which can make calculation speed faster, calculation precision higher and protracting figure easier. On the basis of formulae (1)–(15) and the flowchart, a program written by MATLAB language was used to

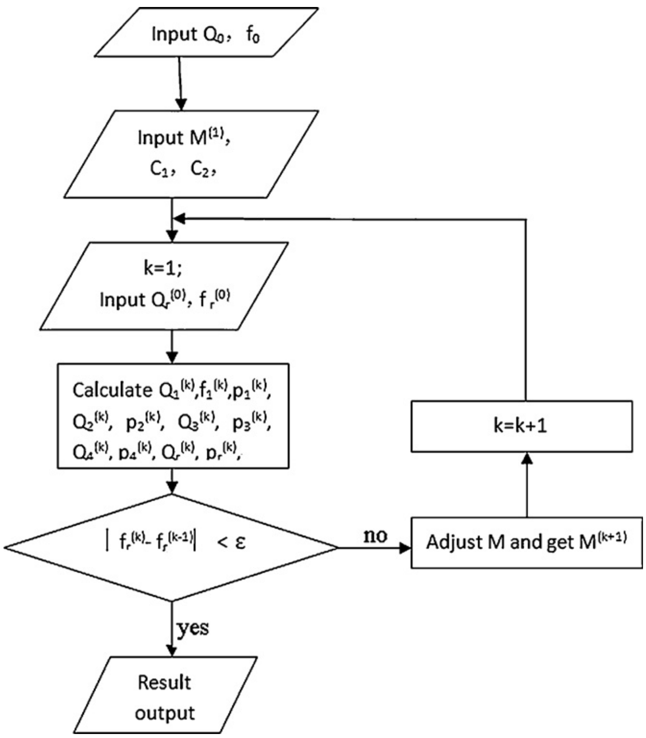


**Fig. 5.** Flow chart of the program for computing model.

compute and plot the waste PCBs particles grinding and classification cyclic system. Fig. 5 shows the entire process of computing model. In the process, from the start of the system to balance, each material flow and particle size distribution can be calculated out.

## 3. Experiment materials and methods

In order to compare with simulation result and collected modeling experience data, 1000 kg of waste PCBs were collected from local PCBs factory (without electronic elements). The weight content of copper of materials was about 20%. Artificial feeding method was adopted to keep feeding rate stable.

On the premise of keeping the production line in a stable operation condition as well as possible, the PCBs particles were collected from needed part of the grinding and classification cyclic system. The sample materials collected from the circuit system were screened by a laboratory electric shaker. Because the incoming particle size of the cyclic system are smaller than 3.2 mm, on the basis of previous researches, the particle grade is divided into seven levels: 1# (0–0.15 mm), 2# (0.15–0.3 mm), 3# (0.3–0.45 mm), 4# (0.45–0.6 mm), 5# (0.6–0.8 mm), 6# (0.8–1.25 mm), and 7# (1.25–3.2 mm).

Grinding matrix of the grinder, classification matrix of cyclone and classification matrix of vibrating screen in the simulation model were acquired from experience data of the industrialized production line. These important parameters were applied in the model analysis, and the obtained simulation results were compared with the actual data collected from the industrialized production line. Materials collected from grinding and classification cyclic system are shown in Fig. 4.

## 4. Results and discussion

### *4.1. Contrast of simulation result and the practical industrial production line*

In order to examine the validity of simulation calculation, the sample of production $Q_2$, $Q_4$, $Q_r$ particles in waste PCBs production line was collected when the system is in stable operation, and particle size distribution was measured. Material feeding speed of the production line was maintained in 100 kg/h and artificial feeding was used to guarantee the stability of feeding speed. Fig. 6 shows the comparative analysis of practical value and simulation value in key parts.

From Fig. 6a and c, we can find that simulation value and measured practical value showed a good agreement for the size distribution of cyclone output material and system backflow material, although there was a little positive deviation. But for the underflow material of vibrating screen which also can be seem as feeding material of electrostatic separator, small grade particles (−0.5 mm) in simulation were more than practical while big grade particles (+0.5–1.25) were less. As the dotted line depicted (Fig. 6a, c and e), the cut diameters of simulation and practical were nearly unanimously the same, which proved the effectiveness of the model in a certain extent.

Analysis $Q_2$ of the cyclone separator, for particle size grade 1# (−0.15 mm), the mass fraction of simulation was 51.6% while practical was 49.4%. And simulation value and practical value were very close. Size grade 1# takes half of the $Q_2$ material, so the simulation result of this grade is critical to the $Q_2$ simulation effect. Meanwhile, grade 2–7# were analyzed in contrast, mass fraction of every grade was about 9% and simulation result was good.

Analysis $Q_4$ of the vibrating screen, there were two peaks of simulation mass fraction which located in grade 1# and grade 5#, and the peak of practical mass fraction located in grade 1#, 4# and 5#. If grade 4# and 5# were added, the simulation and practical content of size +0.45–0.8 mm particles were very close, respectively, 49.5% and 43.9%.

Analysis $Q_r$, which flows from the screen back to the hammer grinder (Fig. 6e and f), grade 6# particles accounted for most, and the mass fraction of simulation and practical were, respectively, 79.3% and 86.7%. Grade 2–4# particles were too few to be measured. In theory, grade 1# particles should flow into underflow material of vibrating screen because its particle size is very small, but here existed about 3%. Two reasons can probably explain this phenomenon: (1) particle size is too small and become floater, so some particles flow into backflow material under the effect of airflow; and (2) in the process of screw conveying, collision occurs between particles or between particle and mechanical equipment, which caused some particles cracked into smaller particles.

From what we have discussed above, we can make the conclusion that the model simulation value has a slight difference with industrial production line. But if instable working condition of industrial production equipment and complexity of environmental factors are considered, this model can be considered to be valid. The model can be used for the analysis of the grinding and classification cyclic system, and for a further hierarchy it can provides a basis for the automation process control of waste PCBs production line [16].

### *4.2. Model applied to analysis the dynamic balance process*

Because many variables are difficult to measure in real industrial production process, we can use the model to simulate the whole process, and analyze the dynamic process of material from imbalance to balance.

The feeding material was 100 kg each time, and the backflow product material increased gradually along with the cycle continuously, but the increasing range reduced gradually and reached a steady value eventually. 6 cycles were simulated and the results were recorded to make a change trend chart (Fig. 7). The simulation results showed that a stable equilibrium can be achieved after 3 cycles. Time is very short for 3 cycles, so the system is considered to be anti-jamming.

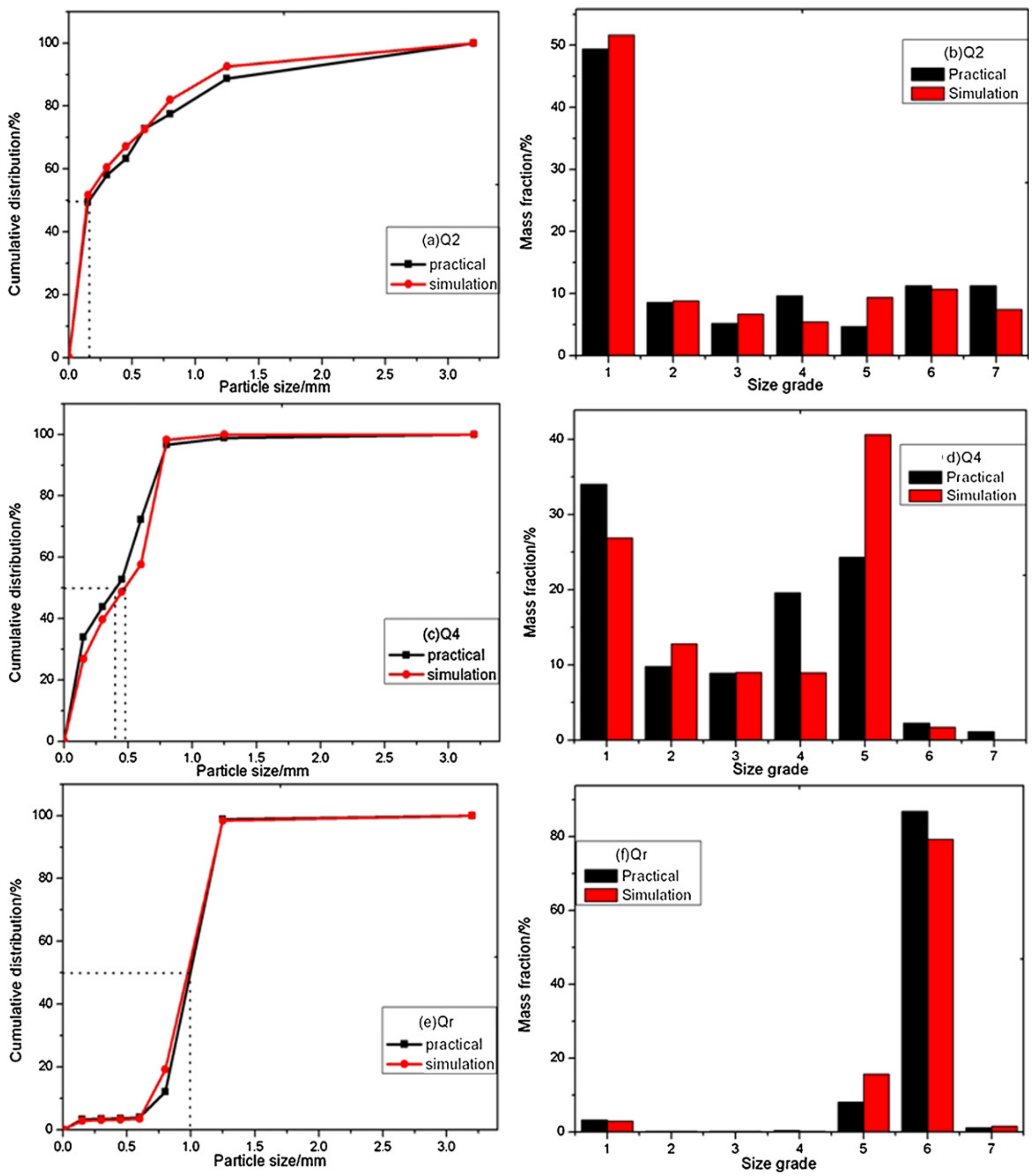


**Fig. 6.** Contrast of practical value and simulation value in key parts: (a) light output material cumulative distribution in cyclone separator: $Q_2$; (b) mass fraction of different size grade in light output material: $Q_2$; (c) underflow material cumulative distribution of vibrating screen: $Q_4$; (d) mass fraction of different size grade in vibrating screen underflow material: $Q_4$; (e) backflow material cumulative distribution of vibrating screen: $Q_r$; and (f) mass fraction of different size grade in vibrating screen backflow material: $Q_4$.

As shown in Fig. 7a, grade 1# material is about 20 kg, and other grades are very little. The volatility of each grade is not big, which shows cyclone has a very good effect, therefore the load of the following electrostatic separation process is reduced and the efficiency of the production line is improved. As shown in Fig. 7b, grade 5# material is the most, and the volatility is the largest. This shows vibrating screen has a good effect, and the feeding stability of electrostatic separation is assured. Meanwhile, attention should be paid that there also exist many grade 1# material. After observing the collected materials for production line, we found that the metallic content is relatively larger in grade 1#, which shows that cyclone has a certain effect on small non-metal and metal particles separation. As shown in Fig. 7c, grade 6# particle is about 25 kg and it is far more than other grades. The volatility of all grades is small, the particles which are not fully comminuted backflow in a good condition, and the excessive crushing rate is in a good control.

### 4.3. Ratio variation analysis

To discuss material flow relationships in each part, proportional relationships of main material flow in the system were analyzed. As the feeding material of the whole system be a benchmark, we define cyclone discharging ratio $R_2 = Q_2/Q_1$, vibrating underflow ratio $R_4 = Q_4/Q_1$, and backflow ratio $R = Q_r/Q_1$. From the simulation data of 100 kg feeding material each cycle, we drew ratio change trend as Fig. 8. The cyclone discharging ratio changed from the beginning of the 0.329 to the stable value of 0.404, and the growth rate was 22.8%. The vibrating underflow ratio changed from the

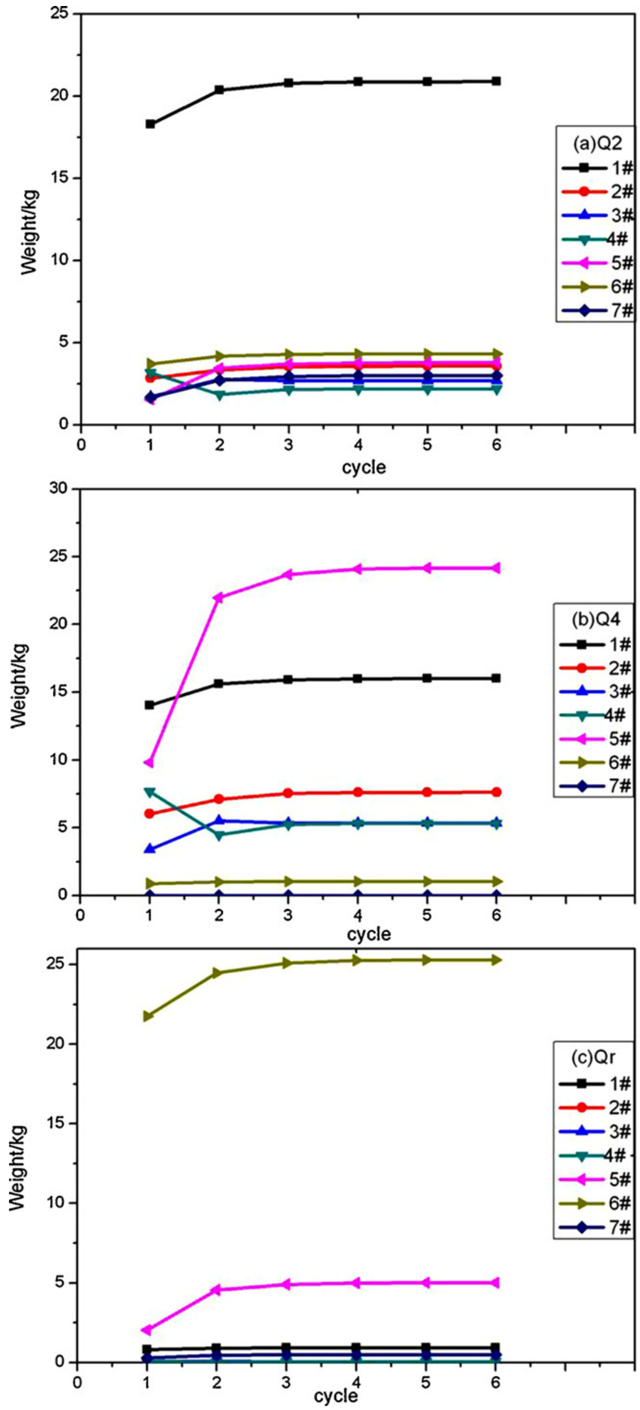


**Fig. 7.** The material weight changing trend in each grade: (a) the cyclone output material: $Q_2$; (b) the vibrating screen underflow material: $Q_4$; and (c) backflow material: $Q_r$.

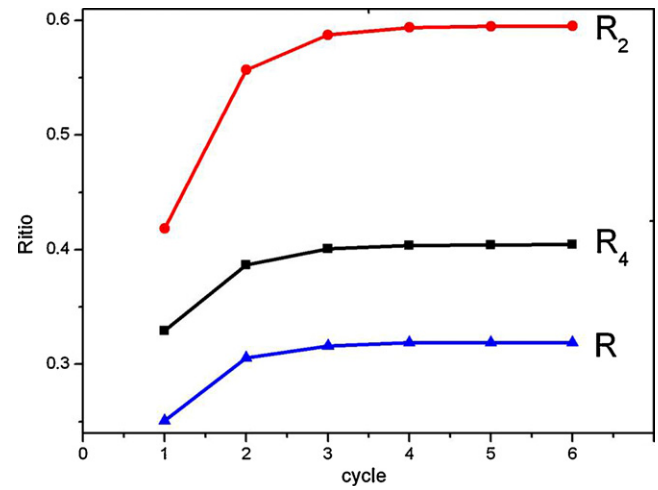


**Fig. 8.** Material flow ratio in each cycle.

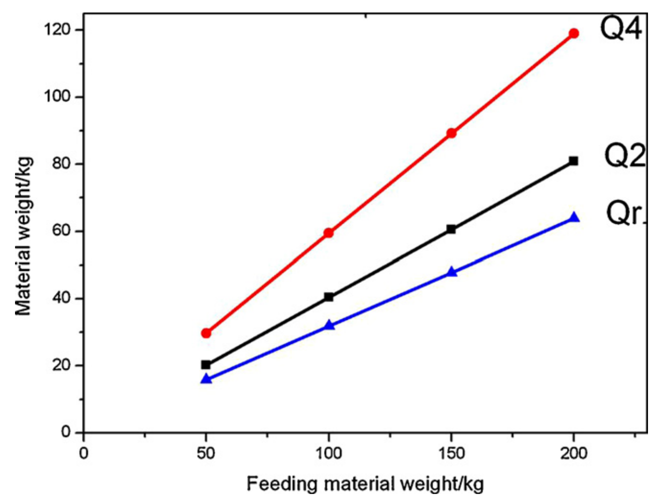


**Fig. 9.** Material weight according to different feeding weight.

beginning of the 0.418 to the stable value of 0.595, and the growth rate was 42.3%. The backflow ratio changed from the beginning of the 0.251 to the stable value of 0.319, and the growth rate was 27.1%. So when the feeding material is in an unstable situation, the volatility of vibrating underflow material is big, and relatively the volatility of cyclone discharging material and backflow material is small.

For analysis of material flow relationship with feeding material, different weight feeding materials were generated into the model, value of the material weight in each part was obtained after the system was in balance. Without doubt, the material flow weight was not beyond the disposal load of these equipments. We got material change values as Fig. 9, and we can clearly see that $Q_2$, $Q_4$ and $Q_r$ is proportional to the feeding material weight. The cyclone discharging slope is 0.404, the vibrating underflow slope is 0.595, and the backflow slope is 0.319. Therefore, the vibrating underflow slope and the volatility of vibrating underflow are the biggest, which have a good agreement with the above verdict.

## 5. Conclusion

(1) A grinding and classification matrix model for waste PCBs automatic production line was built. By contrast with actual production line, the validity of the model was verified. The model provides a good foundation for automatic process control of the production line.
(2) The model was applied for steady-state analysis of the production line, it was found that only 3 cycles are needed for the equilibrium of the production line, which indicated that the production line have a strong adaptability.
(3) The model was applied for analysis according to different weight of feeding materials, material flow in each part presented a linear relationship with the feeding material.

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## References

[1] K. Huang, J. Guo, Z. Xu, Recycling of waste printed circuit boards: a review of current technologies and treatment status in China, J. Hazard. Mater. 164 (2009) 399–408.
[2] J. Cui, E. Forssberg, Mechanical recycling of waste electric and electronic equipment: a review, J. Hazard. Mater. 99 (2003) 243–263.
[3] M. Hugo, M. Andrea, Z. Jane, F. Celia, Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy, J. Hazard. Mater. 137 (2006) 1704–1709.
[4] J. Li, Z. Xu, Environmental friendly automatic line for recovering metal from waste printed circuit boards, Environ. Sci. Technol. 44 (2010) 1418–1423.
[5] J. Li, H. Lu, J. Guo, Z. Xu, Y. Zhou, Recycle technology for recovering resources and products from waste printed circuit boards, Environ. Sci. Technol. 41 (2007) 1995–2000.
[6] J. Wu, J. Li, Z. Xu, Electrostatic separation for multi-size granule of crushed printed circuit board waste using two-roll separator, J. Hazard. Mater. 159 (2008) 230–234.
[7] H. Lu, J. Li, J. Guo, Z. Xu, Pulverization characteristics and pulverizing of waste printed circuit boards (printed wiring boards) based on resource utilization, J. Shanghai Jiaotong Univ. (4) (2007) 551–556 (in Chinese).
[8] J. Wu, Y. Qin, Q. Zhou, Z. Xu, Impact of nonconductive powder on electrostatic separation for recycling crushed waste printed circuit board, J. Hazard. Mater. 164 (2009) 1352–1358.
[9] S. Hou, J. Wu, Y. Qin, Z. Xu, Electrostatic separation for recycling waste printed circuit board: a study on external factor and a robust design for optimization, Environ. Sci. Technol. 44 (2010) 5177–5181.
[10] J. Wang, Q. Chen, Y. Kuang, A.J. Lynch, J. Zhuo, Grinding process with in vertical roller mills: experiment and simulation, Min. Sci. Technol. 19 (2009) 97–101.
[11] H. Benzer, L. Ergun, M. Oner, M.A.J. Lynch, Simulation of open circuit clinker grinding, Miner. Eng. 14 (2001) 701–710.
[12] A.J. Lynch, Mineral Crushing and Grinding Circuits: Their Simulation, Optimization Design and Control, Elsevier, 1977, p. 340.
[13] J.Liu, A general model for the simulation of closed-circuit comminution process, Min. Metall. 14 (2005) 23–30 (in Chinese).
[14] L.G Austin, P.T. Luckie, D. Wightman, Steady-state simulation of a cement-milling circuit, Int. J. Miner. Process. 2 (1975) 127–150.
[15] A.J. Lynch, M. Oner, H. Benzer, Simulation of a closed cement grinding circuit, Zem. Kalk Gips 53 (2000) 560–567 (English translation).
[16] B. Michaël, V.W. Alain, L. Renato, R. Christine, R. Marcel, Modeling and control of cement grinding processes, IEEE Trans. Control Syst. Technol. 11 (2003) 715–725.