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An environmental friendly recovery production line of waste toner cartridges

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ABSTRACT

Quantity of waste toner cartridges has been generated following the increasing demand for printer and duplicator. Waste toner cartridge contains abundant valuable metals, plastics as well as toxic residual toner. Therefore, the recovery of waste toner cartridges is a meaningful subject, not only from waste treatment but also from environment protection. This study proposed a mechanical production line for recovering waste toner cartridges. The recovery process involved shearing process, magnetic separation, and eddy current separation. The recovery rates of steel (magnet), toner, aluminum, and plastic were 98.4%, 95%, 97.5%, and 98.8%, respectively. The results of the comparison between the production line and full manual dismantling indicated that the production line succeed in recovering waste toner cartridges. In addition, the proposed production line is an efficient and environmental friendly way for recovering waste toner cartridges.

1. Introduction

The replacement of electrical and electronic equipment resulted of technological innovation and market expansion leads to a significant generation of electronic waste (e-waste) in worldwide, such as PCs, mobile telephones, and household electrical appliances, etc. In west Europe, 6 million tonnes of e-waste were generated in 2003, the amount of e-waste increased by at least 3–5% per year. In the USA, over 315 million computers had been at end of their life in 2004 [1]. In 2006, the world's production of e-waste was estimated at 20–50 million tonnes per year, with most e-waste being produced in Europe, the United States and Australasia. China, Eastern Europe and Latin America will become major e-waste producers in the next ten years [2]. The mass-produced of e-waste have been deeply concerned by Chinese and the government. The statute of "waste electrical and electronic equipment recycling management regulation" was promulgated in China in the year of 2008. It not only commands recycling of e-waste must aim at resources reutilization, environment protection, labor safety, and health security but also avoids obsolete and polluted technology for recycling e-waste. Although the government and origin entrusted manufacture have made great efforts on refilling, refurbishing, and remanufacturing the used toner cartridges, the number of discarded toner cartridges has been sharply increasing. In 2009, about 4 tonnes waste toner cartridges were collected in XinJinqiao Industrial Waste Management Co., Ltd. in Shanghai China. The reclamation of waste toner cartridges has been an urgent project on waste solid treatment. In order to find a successful recovery technology, this paper studied the components of different waste toner cartridges from ink jet printer cartridges, laser printer cartridges, and duplicator cartridges. One hundred of waste toner cartridges were manual dismantled in lab. Fig. 1 presents the manual dismantling process as well as the average proportion of each comprised material. The materials (steels, aluminums, plastics, and magnets) should be recovered and reused as raw industrial materials. Toxic toner should be collected and sent to specialist agency for better treatment. The composition of toner is presented in Table 1. Organic macromolecular compounds are the main component of toner which may pollute environment or threat human health if leaked out. Furthermore, many tinpot toners contain polycyclic aromatic hydrocarbon and dimethyl nitrate amine (both are carcinogen) as the imaging materials. Therefore, how to recover waste toner cartridges is an important topic not only from resource reutilization but also from environment protection. Landfill and incineration are not suitable for dealing with waste toner cartridges. The reasons are: (1) the plastics made of engineering grade polymers have a very slow decomposing rate in environment or furan and dioxin gases may be produced in incineration; (2) residual toner will leak out so as to pollute the environment in the treatment of landfill or incineration.

Mechanical method has been regarded as the preferable recovery technology for e-waste since no secondary pollution was brought out during the process [3–7]. Magnetic separation has been widely used in mineral processing or solid waste industry to recover magnetic materials from other materials [8]. Eddy current separation has been applied for recovering the non-ferrous metals (Cu, Al, Pb, and Zn) from the solid wastes or electrical and electronic equipment [9–16]. According to the different magnetism

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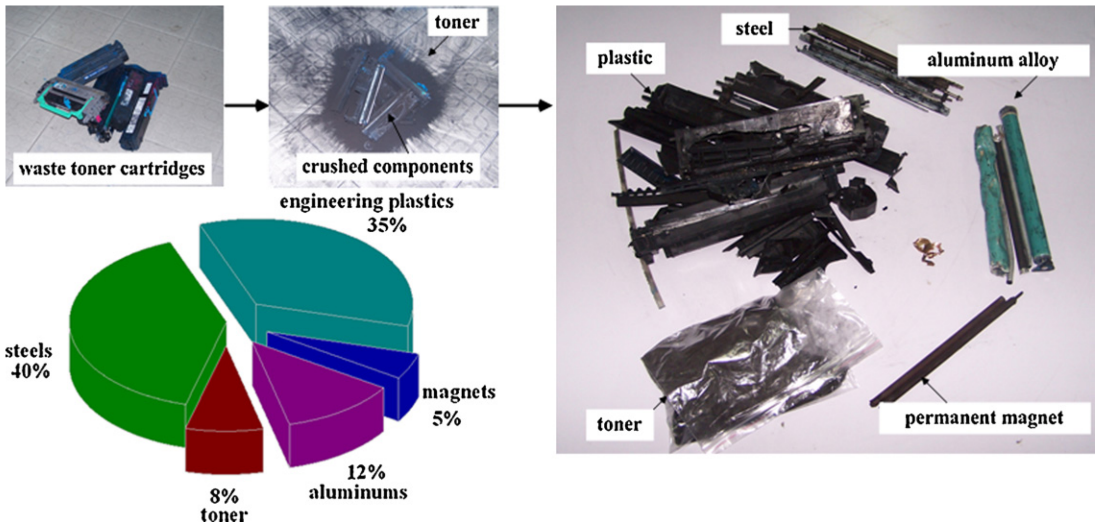

Fig. 1. The manual dismantling process of waste toner cartridges and the material proportions.

Table 1
The composition of toner in waste toner cartridges.

Composition	Material	Function	Proportion (wt%)	Size (μm)	Toxicity[b]
Carbon black	Polyacrylate-styrene copolymer	Imaging material	50–60		High
Magnetic powder	Fe_3O_4	Transporting toner	20–30		None
Resin[a]	Polyethylene/polypropylene paraffin wax	Controlling the melting point of toner	2–4	8–12	High
Charge control agent	Hydroxyl-aromatic-acid and the derivatives	Controlling the charge of toner	10–20		High
Additive	SiO_2	Improving the fluidity of toner	1–3		None

[a] Refined from oil.
[b] Inhaled into human body due to the small size.

and conductivity of the comprised materials, we proposed a combined mechanical separation technology to recover waste toner cartridges. The flowchart is presented in Fig. 2. Coarse crushing process was employed to liberate waste toner cartridges. Bag-type dust collector connected with the shearing machine was designed for collecting residual toner during shearing process. Magnetic separation was employed to separate steels and magnets from aluminums and plastics. Aluminums and plastics were supposed to be separated by eddy current separation depending on their quite different conductivities.

2. Materials and methods

2.1. Materials

This study involved 500 kg waste toner cartridges obtained from Industrial Waste Management Co., Ltd. in Shanghai China. As shown in Fig. 1, the largest board size used was 300 mm × 150 mm × 100 mm and the smallest size was 250 mm × 100 mm × 80 mm.

2.2. Methods

2.2.1. Shearing process

Coarse shearing was used to liberate the materials of waste toner cartridges. Shearing quality depended on particle physical characteristics including hardness, strength, caking property, and particle size [17]. The comprised materials of waste toner cartridge have great two-dimensional scale, great hardness, and large particle size. Thus hammer grinder with knives is chosen to the shearing process since shear force and impulsive force are more suitable for crushing waste toner cartridges. In addition, according to the previous study [18], the experimental equation for energy consumption is:

$$E = 2340 \cdot m \left(\frac{1}{D_2} - \frac{1}{D_1} \right) \quad (1)$$

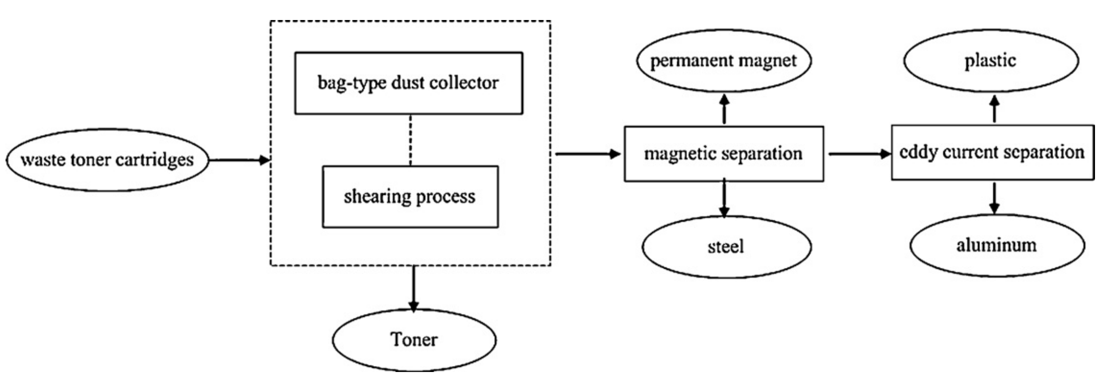

Fig. 2. The flowchart of the waste toner cartridge recovery process.

where m is the mass of waste toner cartridges, D_1 is the average size of waste toner cartridge particles before scraping, and D_2 is the average size of waste toner cartridge particles after scraping. So the energy consumption is decided by the average size of particles. The diameter of screen hole not only impacts the liberation of waste toner cartridges but also determines the energy consumption. If the diameter of the screen hole is too small, having little effects on the liberation grade, the crushing process will cost more energy consumption. The process of shearing released much energy and increased the temperature inside shearing machine. The high temperature environment not only accelerates the abrasion of shearing machines, but also increases the possibility of waste toner cartridges (plastic) pyrolysis. To avoid the above problems, the rotating speed of knives in hammer grinders must be controlled. But slowing the speed too much will reduce the liberation grade of waste toner cartridges.

2.2.2. Toners collection

Bag-type dust collector connected with the shearing system was designed to collect toners during shearing process. The collection and shearing system was well sealed in order to prevent the toner leaking into the environment.

2.2.3. Magnetic separation

Magnet separator was employed for separating steels and magnets from waste toner cartridges. Magnet materials can be easily separated from the crushed waste toner cartridges. Steels also can be separated by magnetic separation if the magnetism force (F_m) is greater than gravity (G). Magnetism force is expressed as [19]:

$$F_m = m\frac{1}{\mu_0}xB\text{grad}B; \quad f_m = \frac{1}{\mu_0}xB\text{grad}B \tag{2}$$

Gravity force is calculated by:

$$G = mg \tag{3}$$

where m is mass of particle (kg); μ_0 is permeability of vacuum (N/A^2); x is the relative magnetic susceptibility of the particle (m^3/kg); B is the magnetic flux density of magnetic field (T); grad$B$ is the gradient of magnetic flux density (T/cm); f_m is the magnetism force acceleration; G is gravity force; g is gravity acceleration (N/kg). The relative magnetic susceptibility of steel is greater than 38×10^{-6} cm^3/g. We measured the magnetic flux densities in per 5 mm leaving from the separator surface on the vertical direction by teslameter. Magnetic flux density (B) and Density gradient (grad$B$) of magnet were about 0.24 T and 0.15 T/cm. The value of vacuum permeability (μ_0) is $4\pi \times 10^{-7}$ N/A^2. So, the calculation of f_m is 1089 N/kg which was greater than the gravity acceleration (9.8 N/kg). The applied magnetic separator can separate the steels and magnets from the crushed waste toner cartridges successfully. The schematic diagram of magnetic separation was presented in Fig. 3. Ferromagnetic materials were collected in tank A resulting from the action of magnetic force and gravity force. The nonmagnetic materials (aluminum and plastic) were only subjected to gravity force in magnetic separation and collected in tank B.

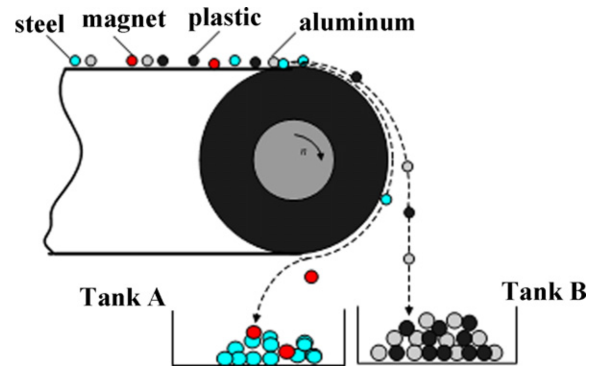

Fig. 3. The schematic diagram of magnetic separation for recovering steels from waste toner cartridge.

2.2.4. Eddy current separation

The horizontal eddy current separator was employed to recover aluminums and plastics from waste toner cartridges. Eddy current separation quality is determined by the different movement trajectories of particles. Although the physical characteristic (size, conductivity, shape, orientation) and operating factors (feeding speed or mode, magneticfield period) will affect the separation quality [14], interaction between eddy current (induced in the nonferrous particle) and magnetic field is the most important influencing factor for changing the trajectory of nonferrous metal as well as separating them from others. When nonferrous metal was moving close to dynamic magnets, current will be induced in metal and an induced time-depended magnetic field is also produced in metal immediately. The movement of nonferrous metal is considered in two-dimension space and instantaneous state. The induced magnetic field in the metal has the same vector orientation of magnetic flux to the inducing magnet. This phenomenon can be explained as: according to lenz law, the induced magnetic field in the aluminum flake has the orientation N when it meeting the inducing

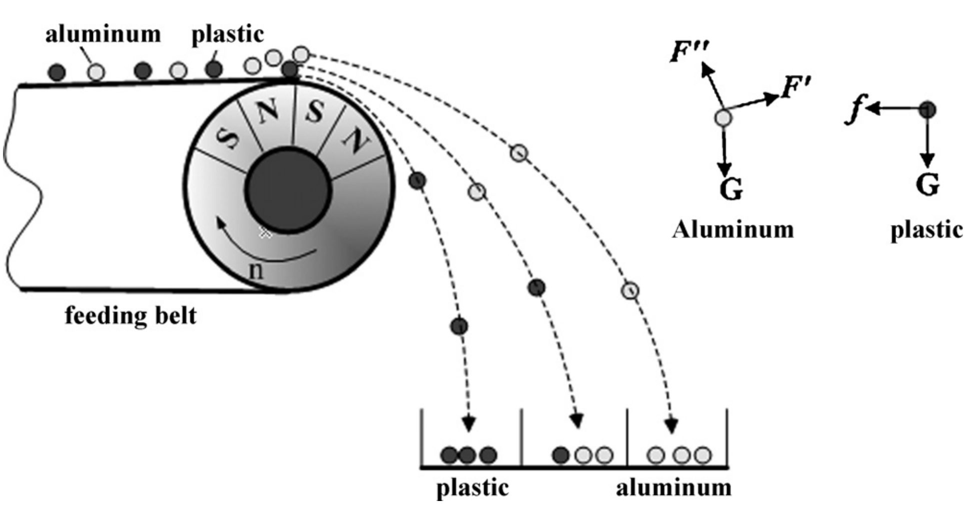

Fig. 4. The trajectories of aluminum and plastic flakes as well as the dominative forces in eddy current separation.

magnet with N orientation. Repulsive force F' (Fig. 4) will be generated between nonferrous metal and inducing magnet because of the same vector of magnetic flux. Meanwhile, attractive force F'' was also generated between nonferrous metal and other magnet that next to the inducing magnet in clockwise due to the opposite vector orientation of magnetic flux. So eddy current force is considered as the resultant of compulsive and attractive force. We neglect the vertical component of attractive force and the horizontal component of repulsive force since their small value. Then we consider the nonferrous metal particle subjected to horizontal attractive force and vertical repulsive force. When the vertical repulsive force is greater than the gravity force, the particle will leave from the belt and levitate to be accelerated forward acted by the horizontal attractive force. The particle is considered as "Magnetically Levitated Train" in this process. Particles should be fed into the eddy current separator monolayer in order to reduce the interaction between particles. Thus inter-particle force is supposed to be negligible considering the co-acting forces. Nonmetal particle is subjected to gravity (G) force, air friction force and sliding friction (f) force when detaching from the external shell. Compared to the other acting forces, air friction force and sliding friction force are assumed to be negligible due to the light effects on the trajectory of the particle. So, after leaving the external shell, the trajectory of nonmetal particle is determined by gravity force only. Different from nonmetal, the trajectory of nonferrous metal particle is determined by repulsive force, attractive force, and gravity force. Repulsive force made nonferrous metal particle levitated if greater than gravity force. Attractive force accelerates the particle in horizontal direction. The resultant of the two forces made the trajectory of nonferrous particle different from nonmetal particle. Fig. 4 portrayed the trajectories of two kinds of particles as well as the dominative forces. Nonferrous metal particle will have a farther displacement in the horizontal direction. It makes the nonferrous metal particle separated from nonmetal.

3. Results

3.1. The production line and recovery results

A production line for recovering waste toner cartridges was constructed in enterprise based on the above proposed recovery process. The flowchart of recovery industrial production line was presented in Fig. 5. The production line was comprised of shearing machine, agitator, bag-type dust collector, magnetic separator, eddy current separator. The materials (permanent magnet, steel, plastic, aluminum, and toner) were recovered in different steps when waste toner cartridges undergoing recovery production line (seen Fig. 5). The whole recovering line was automotive and well sealed (bag-type dust collector connected with shearing machine and agitator by sealed pipe, all over the belt conveyor were enclosed). These designs not only improved the recovery capability of the production line but also prevented the toner leaking into environment. For the purpose of studying the capability of the recovery production line, we fed 500 kg waste toner cartridges into the production line. The processes of the recovery production line were discussed in the following parts.

Step I (shearing process): By the work of belt conveyor I (Fig. 5), waste toner cartridges were fed into shearing machine. The diameter of the screen hole was designed about 15 mm since waste toner cartridges would not have a good liberation until they were crushed below 15 mm size. In addition, if the diameter of the screen hole was smaller than 15 mm which had little contribution to better liberation of waste toner cartridges, the shearing process would cost more energy consumption according to Eq. (1). To avoid the abrasion of shearing machines and the pyrolysis of waste toner cartridges (plastic) that induced by the high temperature inside shearing machine (shearing process released vast energy), the rotating speed of knives in hammer grinders was controlled to 1800 rpm. The circulating water system that fixed on the hammer grinders controlled the temperature inside the machine to 80 °C when the machines were running at full capacity. After shearing process for waste toner cartridges, the comprised material were crushed into flake granule with sizes concentrating on $10 \times 10 \times 1$–$15 \times 15 \times 2$ mm (Fig. 5). Reclaimed materials after the shearing process included steel, magnet, aluminum, plastic, and toner. Toner was collected by the bag-type dust collector through the well sealed pipe during this process. 38 kg toners were collected by the bag-type dust collector (Fig. 5).

Step II (magnetic separation process): Belt conveyor II (Fig. 5) fed the mixed flakes (magnet, steel, aluminum, and plastic) into magnetic separation process. Rotation speed of the magnetic separator may impact the magnetic separation quality [20]. In order to find the optimize operation parameters, magnetic separation experiment was studied. The results were presented in Table 2. It can be seen from Table 2 that all over the steel and magnet particles were collected in steel and magnet collector (Fig. 5). However, nonferrous and nonmetallic particles were in the steel collector at low feeding speed. It mainly because of horizontal ranges of nonferrous and nonmetal particles were determined by the initial speed. The proportion of plastic and aluminum in steel collector were decreased as the feeding speed increasing. High feeding speed brought better magnetic separation quality. When the feeding speed reached 350 rpm, steel-magnet particle were separated completely. Thus,

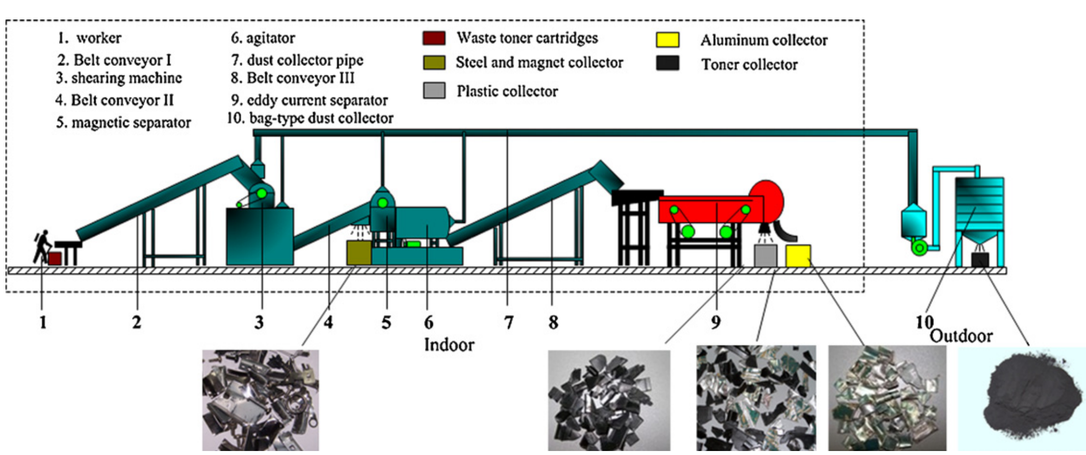

Fig. 5. The flow chart of industrial production line for recovering waste toner cartridges.

Table 2
The separating results of magnetic separation in recovery line.

Feeding speed (rpm)	Tank A (wt%)			Tank B (wt%)		
	Steel and magnet	Plastic	Aluminum	Steel and magnet	Plastic	Aluminum
40	100	84.7	66.2	0	15.3	34.8
100	100	40.6	41.5	0	59.4	49.5
180	100	19.5	30.8	0	80.5	69.2
250	100	12.1	14.6	0	87.9	85.4
320	100	2.8	0	0	97.2	100
350	100	0	0	0	100	100

we controlled the rotation speed of the magnetic separator at 350 rpm. About 221.5 kg particles were collected in steel collector and few plastic or aluminum flakes existed in the collector. After magnetic separation process, an agitator was employed to make the flakes stayed on the belt monolayer which would bring better quality for eddy current separation. Meanwhile, another application of the agitator was to make toner detached from the particles (aluminum, and plastic) in order to collect toner furthest. Seen from the obtained flakes (Fig. 5), there were little toner adhered to the surface of the flakes after agitating process.

Step III (eddy current separation process): Belt conveyor III (Fig. 5) fed the aluminum and plastic flakes into eddy current separation. The quality of eddy current separation is determined by operating parameters (feeding speed and rotation speed of eddy current separator) and particle physical characteristic (size, shape, conductivity, orientation, and contamination). In eddy current separation process, the physical characteristics of aluminum and plastic flakes were determined by shearing process. Though there were different type plastics in waste toner cartridges, classified by the conductivity, the plastic variety had no impact on eddy current separation quality. The operation parameters were the main impact factor to eddy current separation quality. In order to obtain optimized operating parameters, eddy current separation experience was studied. The mass proportion of the flakes was computed by the following equation:

$$\eta = \frac{M}{M_{(\mathrm{Al+Pl})}} \times 100\% \quad (4)$$

where M is the flake mass contained in collector, $M_{(\mathrm{Al+Pl})}$ is the total mass of aluminum and plastic flakes in eddy current separation. The experience results were given in Table 3. Feeding speed and rotation speed of magnetic field influenced the separation results. High rotation speed of magnetic field increased the separation quality. When the rotation speed reached 800 rpm along with feeding speed 40 rpm, the recovery rate of aluminum particles was 97.9%. In addition, no plastic particles were found in aluminum collectors. The recovery rate of aluminum particle was increased as the increasing of feeding speed. When feeding speed reached 100 rpm as well as the rotation speed of magnetic field 800 rpm, the recovery rate of aluminum reached 99.7%. However, about 10.9% of plastic were in the aluminum collector. Thus, high feeding speed was not suitable for separating nonferrous materials. In production line of recovering waste toner cartridges, feeding speed 40 rpm and rotation speed of magnetic field 800 rpm were the optimize operation parameters for eddy current separation. 58.5 kg flakes were obtained in aluminum collector, and 173 kg flakes were obtained in plastic collector. According to the obtained masses of every material, we calculated the recovery rate of every material of waste toner cartridges. Recovery rate (i) was calculated by the formula:

$$i = \frac{M_r}{M_c} \times 100\% \quad (5)$$

where M_r is the mass of the recovered material, M_c was the contained mass of the materials raw in waste toner cartridges. Every recovery rate of the materials had been presented in Table 4. The recovery rates of steel (magnet), toner, aluminum, and plastic were 98.4%, 95%, 97.5%, and 98.8%, respectively. Based on the analysis of the recovery rates, we made the mass balance of waste toner cartridges. The results were given in Fig. 6. Some valuable materials and toner remained in the machine of the recovery production line. Periodic cleaning the production line can recover the remaining materials in machines. The recovery rates of the materials indi-

Table 3
The results of eddy current separation.

ω_f	ω_m	Plastic collecting tank (wt%)		Aluminum collecting tank (wt%)	
		Plastics	Al	Plastics	Al
40	40	100	100	0	0
	150	100	16.1	0	83.9
	300	100	10.5	0	89.5
	450	100	4.8	0	95.2
	600	100	2.1	0	97.9
	800	100	1.1	0	97.9
80	40	94.9	93.3	5.1	6.7
	150	94.5	15.7	5.5	84.3
	300	94.1	5.4	5.9	94.6
	450	94.2	2.2	5.8	99.8
	600	92.6	0.9	7.4	99.1
	800	91.8	0.5	8.2	99.5
100	40	89.2	89.1	10.8	10.9
	150	89.4	9.3	10.6	90.7
	300	87.9	5.1	12.1	94.9
	450	88.6	1.6	11.4	98.4
	600	88.9	0.6	11.1	99.4
	800	90.1	0.3	10.9	99.7

ω_f: the rotation speed of the feeding motor, rpm; ω_m: the rotation speed of magnetic field, rpm.

Table 4
The recovery rates of waste toner cartridges comprised materials by the production line.

Waste toner cartridges	Weight content (wt%) 100	Magnet and steel (wt%) 45	Toner (wt%) 8	Aluminum (wt%) 12	Plastic (wt%) 35
Magnet and steel collector	44.3	44.3	–	–	–
Toner collector	7.6	–	7.6	–	–
Aluminum collector	11.7	–	–	11.7	–
Plastic collector	34.6	–	–	–	34.6
Recovery rate (wt%)	98.2	98.4	95	97.5	98.8

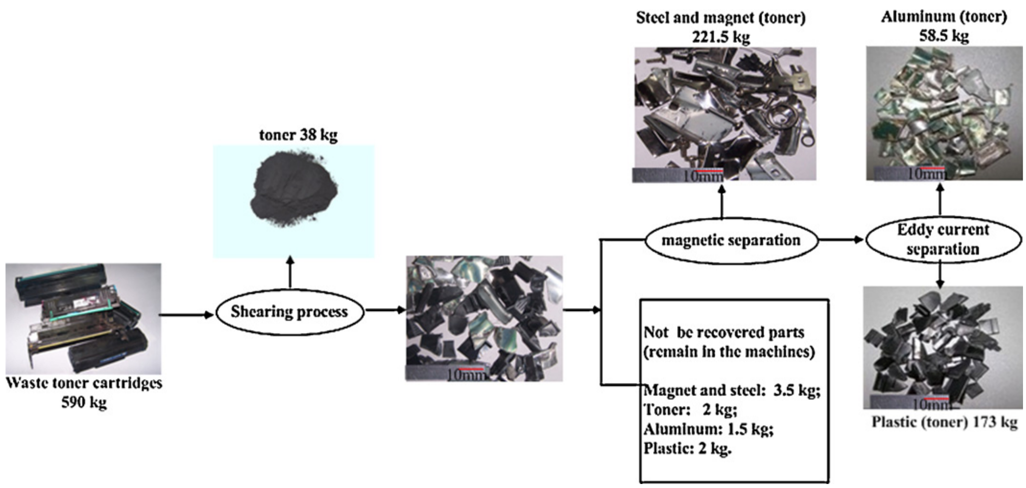

Fig. 6. The mass balance of the materials recovered from waste toner cartridges.

cated that the production line could recovery waste toner cartridges successfully.

3.2. Comparison full manual dismantling to the production line for recovering waste toner cartridges

Based on the experience of manual dismantling in lab and the recovery results of industrial production line, we made an assessment on recovered consumption and work efficiency by comparing the full manual dismantling to recovery production line. 500 kg waste toner cartridges were supposed to be recovered by 100 workers (full manual dismantling) and the proposed production line, respectively. The comparison parts were in follows and the results were given in Table 5:

Recovery capacity: According to the lab experience, dismantling one waste toner cartridges completely would cost 15 min. Waste toner cartridge has the weight of 500–550 g on average. It meant that 100 workers should spend 2.5 h on dismantling 500 kg waste toner cartridges. However, the recovery time of the production line is only an hour and one worker needed.

Economic consumption: The cost of the industrial production line is decided by power consumption of the electric motor (shearing machine, conveyor belt, magnetic separator, eddy current separator, and bag-type dust collector.), the price of the machines, and the payment for the worker (operating the production line). The price of the total machines is about 71.4 thousand dollars. The service life of the production line is about ten years and the work time is about 8 h per day. Thus, the using charge of the production line is 24.45 dollars per hour. The payment of the worker is about 2 dollars an hour in China. Then, economic consumption (i') of the recovery production line is calculated by the formula:

$$i' = (Pt) \times A + 24.45t + 2 \times t \times N \quad (6)$$

where P is the total power of the recovery production line; t is the cost time of recovery process; A is the unit price of electricity in china (0.07 dollar). N is the number of the worker employed for operating the production line. The total power of the recovery production line is about 80 kW. The economic consumption of recovering 500 kg waste toner cartridges by the production line is about 32.05 dollars (only worked an hour). However, in full manual dismantling recovery, the economic consumption of the payment for the workers is about 1500 dollars (worked 2.5 h). Thus, the economic consumption of full manual dismantling is further higher than the recovery production line.

Environment pollution: the environment pollution of recovering waste toner cartridges is determined by the recovery rate of toner. In the production line, the recovery rate of toner had reached 95% and the remained toner was in the sealed well production line (machines or pipe). Little toners were leaked into the environment. However, in full manual dismantling, many toners diffused into environment and were inhaled into human body even if respirator was used. As long as the toner diffused into environment, it is difficult to be collected due to the small size (8–12 μm).

Table 5
The comparison results of full manual dismantling and recovery production line.

Recovery technology	Recovery time (h)	Economic consumption (dollars)	Environmental pollution (recovery rate of toners)
Full manual dismantling	2.5	1500	Low rate and much toners diffused into environment and were inhaled into human body
Recovery production line	1	32.5	95% toners were collected and remained toners were in the sealed well production line

4. Conclusions

Based on theoretical analysis, experience test, and comparison between full manual dismantling to recovery production line, the results indicated that the proposed recovery production line is an efficient, environmental friendly and resource conservation technology for recovering waste toner cartridges. Toner (pollutant) was recovered in an environment friendly way and was sent to the specialist waste treating agent for safety treatment. After coarse shearing process, every comprised material was recovered in different steps of the proposed recovery production line. The metal and nonmetal materials were sent to specialist recycling plant for reusing as raw production materials. The recovery rates of the proposed industrial production line were agreed with the proportions which were obtained by full manual dismantling in lab. Compared to full manual dismantling, the proposed production line increased the recovery capacity waste toner cartridges. Assessment of economic consumption also indicated that it was a cost-saving technology. In addition, the separation methods (magnetic separation, eddy current separation) are the representative application of the technology. Thus, this combined recovery production line for waste toner cartridge is also suitable for recovering other e-wastes composed of ferromagnetic, nonferrous, and nonmetal materials.

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