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Recovery of metals from waste printed circuit boards by a mechanical method using a water medium

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ABSTRACT

Research on the recycling of waste printed circuit boards (PCB) is at the forefront of environmental pollution prevention and resource recycling. To effectively crush waste PCB and to solve the problem of secondary pollution from fugitive odors and dust created during the crushing process, a wet impacting crusher was employed to achieve comminution liberation of the PCB in a water medium. The function of water in the crushing process was analyzed. When using slippery hammerheads, a rotation speed of 1470 rpm, a water flow of 6 m^3/h and a sieve plate aperture of 2.2 mm, 95.87% of the crushed product was sized less than 1 mm. 94.30% of the metal was in this grade of product. Using smashed material graded −1 mm for further research, a Falcon concentrator was used to recover the metal from the waste PCB. Engineering considerations were the liberation degree, the distribution ratio of the metal and a way to simplify the technology. The separation mechanism for fine particles of different densities in a Falcon concentrator was analyzed in detail and the separation process in the segregation and separation zones was deduced. Also, the magnitude of centrifugal acceleration, the back flow water pressure and the feed slurry concentration, any of which might affect separation results, were studied. A recovery model was established using Design-Expert software. Separating waste PCB, crushed to −1 mm, with the Falcon separator gave a concentrated product graded 92.36% metal with a recovery of 97.05%. To do this the reverse water pressure was 0.05 MPa, the speed transducer frequency was set at 30 Hz and the feed density was 20 g/l. A flow diagram illustrating the new technique of wet impact crushing followed by separation with a Falcon concentrator is provided. The technique will prevent environmental pollution from waste PCB and allow the effective recovery of resources. Water was used as the medium throughout the whole process.

1. Introduction

The re-utilization of waste printed circuit boards (PCB) is a focused topic in the field of environment protection and resource recycling [1–3]. Presently, waste PCB is mainly processed using physical methods, chemical methods, biological methods or combinations of these approaches [4]. In the process of reclaiming waste PCB, crushing is the crucial technique. Its importance for chemical and biological methods is that the crushing process must make the surface of the resulting particles appropriate for subsequent contact with the chemical or biological medium. Considering physical methods, the process of crushing may directly affect the efficiency of successive separation steps, which then can affect the recovery rate and the purity of the metal. The circuit board cards commonly found in computers and mobile phones are FR-4 type epoxy glass-cloth copper clad laminate. This is a kind of compound material made from epoxy resin, glass fiber cloth and high purity copper foil.

Because of the strength and tenacity of this material, much dust and harmful gas could be produced in the process of dry crushing at normal temperatures. On the other hand, after very long operation, very high temperatures can develop in the equipment causing melting and jamming of the particles and, hence, reduced efficiency of crushing and environmental pollution too. A way to enhance crushing efficiency and reduce secondary pollution during processing of waste PCB is an important problem. One typical method is to cool the waste PCB below the embrittlement temperature using liquid nitrogen and then crush it [5]. The high cost of low temperature crushing limits its further industrial application. To achieve high crushing efficiency and to resolve the secondary pollution problems of dust and gas from the crushing process, a wet impacting crusher was used to perform comminution of PCB in a water medium. The mechanism of crushing and the function of water during the process of crushing are analyzed. The size distribution of the crushed material and the metal content in each grade are also studied.

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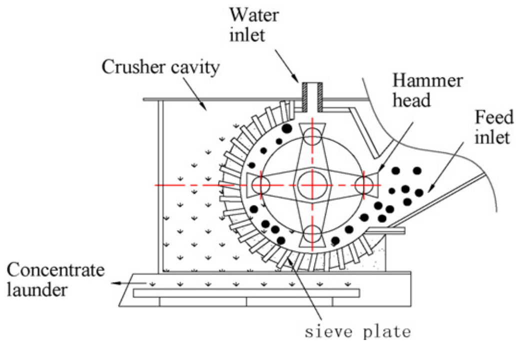

Fig. 1. Sketch of wet impacting crusher.

A Falcon SB40 concentrator, which is a centrifugal separator, was used to recycle metal from waste PCB crushed to less than 1 mm. The mechanism by which fine particles of different densities were separated in the centrifugal concentrator was studied in detail. The processes in the segregation and separation zones were deduced. The main factors that might affect separation were studied: centrifugal acceleration magnitude, anti-charge water pressure and slurry concentration in the feed. Interaction of the factors was analyzed and a recovery model including different factors was established using Design-Expert software. Comprehensive analysis of the diagnostics for each case show the recovery model is accurate. The results show that the Falcon centrifugal separator provides a simple and effective new approach for the re-utilization of metal from discarded PCB.

Thus a new technique of “wet impact crushing + the Falcon separation” was brought forward for recycling metals from waste PCB, which offers one approach to resource recycling and the prevention of environmental pollution.

2. The wet impact crushing of waste PCB

2.1. The principle of the wet impacting crusher

The wet crushing equipment is a hammer mill with a water medium. Its schematic representation is shown in Fig. 1. The design is typical for a hammer mill. Hammers are attached to rotating arms in a way that allows the hammers to swing freely. As the arms rotate inside the drum the swinging hammers contact the feed material at a high speed. This imparts kinetic energy from the hammers to the feed, fracturing the feed in the process. High speed feed particles also fracture when they contact other particles or stationary parts of the mill. Feed that escapes fracture after one impact is hit by the hammers again. In this mill, water is fed into an inlet. This causes the particles to form slurry that carries the broken particles through the sieve plate.

The rotating hammers impart a high speed to the feed material. The rapidly moving material can cause intensive compression of the medium and form a bow wave because the stress diffuses at ultrasonic speeds. An impact load occurs during the period when the material receives a high speed strike. The rapid application of force on the material causes a fast change in momentum. As a result, hammer impact is more effective than applying force in a static state to cause brittle fracture of the material.

2.2. The function of water in the process of crushing

The main functions of water are (A) avoiding the diffusing of dust. (B) Avoiding excessive temperature in parts of the machine during the crushing process. (C) Avoiding gas production by pyrolysis during crushing. (D) Speeding up discharge of crushed material and controlling over-crushing in the process. Compared to dry crushing techniques, wet impact crushing has the advantages of higher crushing efficiency, less over crushing and no secondary pollution. The slurry of ground PCB was pumped to a Falcon separator. The water can be recycled and only a small amount of fresh water need be supplied.

2.3. Experimental details and particle size distribution

The effect of hammer types, hammer rotating speed and the flow of water on the distribution of particles from crushed PCB were studied. Table 1 shows the results from tests when using slippery hammerheads, a rotation speed of 1470 rpm, a water flow of 6 m^3/h and a sieve plate aperture of 2.2 mm. 95.87% of the crushed product was smaller than 1 mm: 94.30% of the metal was in this size range. Former research has shown that metal from the slots on the waste PCB would mostly be liberated in the 5–2 mm grade. This work also showed that 66% and 95% of the base plate metal from the PCB appeared in the −2 and −1 mm grades, respectively. Including the −0.5 mm particle size, liberation of metal was 100% of both the baseplate and the molectron. Using a −1 mm grade for research with the Falcon separator we recovered metal from waste PCB after considering the liberation degree, the particle distribution ratio of the metal and ways to simplify the technology.

3. The separation mechanism of the Falcon separator

3.1. The Falcon SB40 concentrator

The Falcon centrifugal separator separates materials by density. The Falcon SB40 used in these experiments is a highly effective centrifugal separating machine. The core part is a plastic inner vertical rotating drum with a slippery inner wall and an inversely tapered lower part. Its upper section consists of two reflex circle slots. A ring of small holes is drilled so that water can flow into the reflex circle slots and loosen and fluidize the heavy layer, as shown in Fig. 2. The Falcon centrifugal machine separates the heavier material into a separation slot, which consists of a smooth rotating frustum, by exposing it to an acceleration of up to 300 × *g*. The unique trait of

Table 1
Test results from waste PCB wet impact crushing.

Size (mm)	Production rate		Degree of liberation (%)	Metal grade (%)	Distribution ratio (%)
	Weight ratio (%)	Cumulative sum (%)			
2.2–2	0.26	0.26	66.00	22.75	0.19
2–1	3.87	4.13	70.00	44.78	5.51
1–0.5	37.30	41.43	95.00	53.96	63.98
0.5–0.25	13.94	55.37	100.00	38.23	14.01
0.25–0.125	16.87	72.24	100.00	21.05	11.29
0.125–0.074	2.56	74.80	100.00		
<0.074	25.20	100.00	100.00	6.28	5.03
Sum	100.00	–	–	26.51	100.00

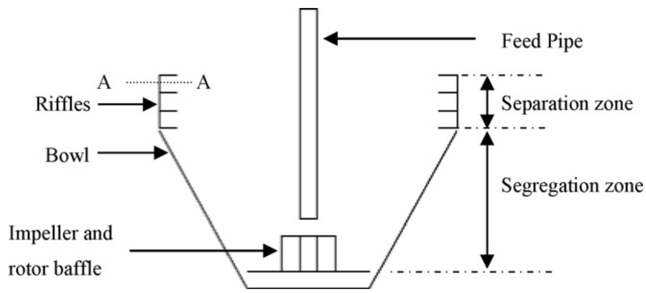

Fig. 2. Sketch of Falcon SB40.

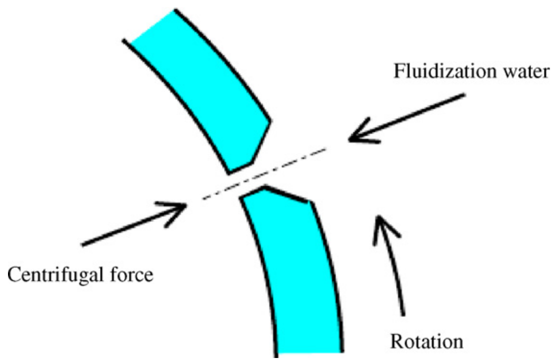

Fig. 3. Local enlargement of water bore in Falcon concentrator PCB particles.

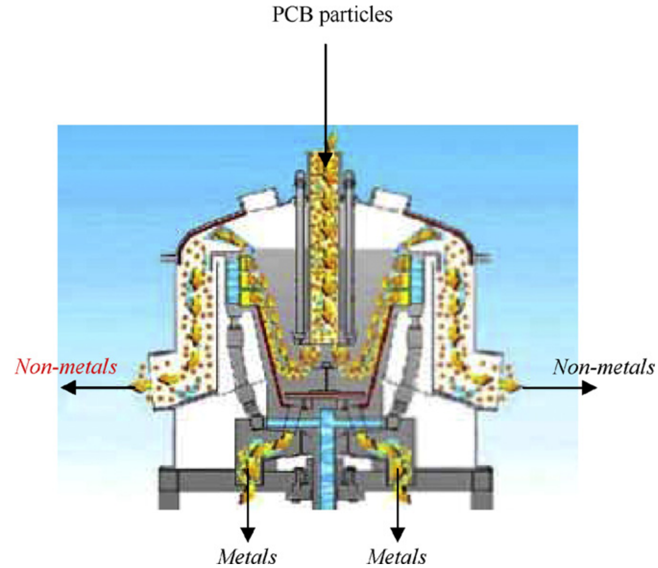

Fig. 4. Schematic diagram of separation process of Falcon separator.

this centrifugal machine is that it uses reverse water to loosen the layer of heavier material and the radial flow direction of the water is opposite the settling direction of particles as shown in Fig. 3 [6].

3.2. *The separation of waste PCB*

Waste PCB ground to a size of less than 1 mm and water were mixed to disperse the particles. The slurry was then pumped to the Falcon feed inlet with a peristaltic pump. After entering the bottom of the inner rotating drum through a guide pipe the feed slurry moves toward the inner wall of the rotating drum because of centrifugal force. At the same time reverse water under some set pressure flows vertically through the holes in the inner wall from a water jacket located between the inside and the outside rotating drums. The water flow fluidizes the material in the reflex circles. Under the opposite effects of centrifugal force and reverse water flow the small grains of higher density metal "sink" to the rotor wall through gaps in the material layer. Even very tiny, high density metal can pass through the layer. But the lower density nonmetallic materials are less affected by the centrifugal force and so the reverse water helps move them out of the inner rotating drum. The effect on the lighter particles is to expel them from the drum with the reverse water to become gangue. The inner rotating drum is unloaded by halting the feed, slowing the rotation speed of the drum and flushing the concentrate into a concentrate trough. This is shown in Fig. 4. The final metal concentrate is filtered. The filtrate can be reused as circulating water.

3.3. *Experimental*

The adjustable parameters of the separating system are feed consistency, feed rate, rotation speed of the drum and reverse water

Table 2
Experimental results from separating −1 mm particles.

No.	Water pressure (MPa)	Rotation frequency (Hz)	Feed concentration (g/l)	Product	Yield%	Grade%	Recovery%
1	0.04	30	10	Concentrate	38.26	84.77	97.12
				Tailing	61.74	1.56	
2	0.04	40	20	Concentrate	35.66	88.42	94.56
				Tailing	64.34	2.82	
3	0.04	50	30	Concentrate	30.32	88.44	93.06
				Tailing	69.68	2.87	
4	0.05	30	20	Concentrate	35.56	92.36	97.05
				Tailing	64.44	1.55	
5	0.05	40	30	Concentrate	32.19	91.12	92.95
				Tailing	67.81	3.28	
6	0.05	50	10	Concentrate	38.52	84.25	96.12
				Tailing	61.48	2.13	
7	0.06	30	30	Concentrate	37.42	79.76	95.71
				Tailing	62.58	2.14	
8	0.06	40	10	Concentrate	28.35	84.36	96.26
				Tailing	72.65	1.28	
9	0.06	50	20	Concentrate	30.55	76.22	91.19
				Tailing	69.45	3.24	

Table 3
Sequential model sum of squares.

Source	Sum of squares	d.f.	Mean squares	*F* value	Prob. > *F*	
Mean	81038.91	1	81038.91			
Linear	26.36	3	8.79	5.32	0.05	Suggested
2FI	4.60	3	1.53	0.84	0.58	
Quadratic	3.66	2	1.83			Aliased
Cubic	0.00	0				Aliased
Residual	0.00	0				
Total	81073.52	9	9008.17			

flow rate. Feed consistency was adjusted by controlling the proportion of feed and water. The feed rate was adjusted by controlling the rotating speed of the peristaltic feed pump. The speed of the rotating drum was adjusted by controlling the input frequency on the control panel of the concentrator. The flow rate of fluidizing reverse water was controlled by adjusting the water pressure. The Falcon SB40 centrifugal machine is a batch machine: The concentrate is unloaded from the drum periodically. The effects of feed consistency, drum rotation speed and the effect of reverse water pressure on metal concentrate recovery were tested in the experiment. The experimental results are shown in Table 2. When the water pressure was 0.05 MPa, the rotation frequency was 30 Hz and the feed density was 20 g/l, we obtained a grade of 92.36% metal in the concentrate and the total recovery was 97.05%. Compared to other ways of separating particles from ground PCB the Falcon centrifugal separator has the advantages of bigger capacity, lower water usage and being able to recover minute size particles.

Table 4
The linear model summary statistics.

S.D.	1.28	R^2	0.76
Mean	94.89	Adjusted R^2	0.62
CV	1.35	Predicted R^2	0.19
PRESS	28.00	Adequate precision	6.20

4. Results and discussion

A “Response-3 Level Design” in Design-Expert 6.08 software was used to analyze the test results and estimate the effects of

Table 5
Diagnostic statistics for the trials.

Standard order	Actual value	Predicted value	Residual	Leverage	Student residual	Cook’s distance	Outlier *T*
1	97.12	97.99	−0.87	0.59	−1.05	0.39	−1.07
2	95.71	96.39	−0.68	0.45	−0.71	0.10	−0.67
3	96.26	95.34	0.92	0.32	0.87	0.09	0.85
4	96.12	95.09	1.03	0.57	1.22	0.50	1.31
5	97.05	95.58	1.47	0.35	1.42	0.27	1.64
6	94.56	95.33	−0.77	0.28	−0.71	0.05	−0.67
7	91.19	92.69	−1.50	0.46	−1.58	0.52	−2.00
8	92.95	92.93	0.02	0.46	0.02	0.00	0.02
9	93.06	92.68	0.38	0.52	0.43	0.05	0.39

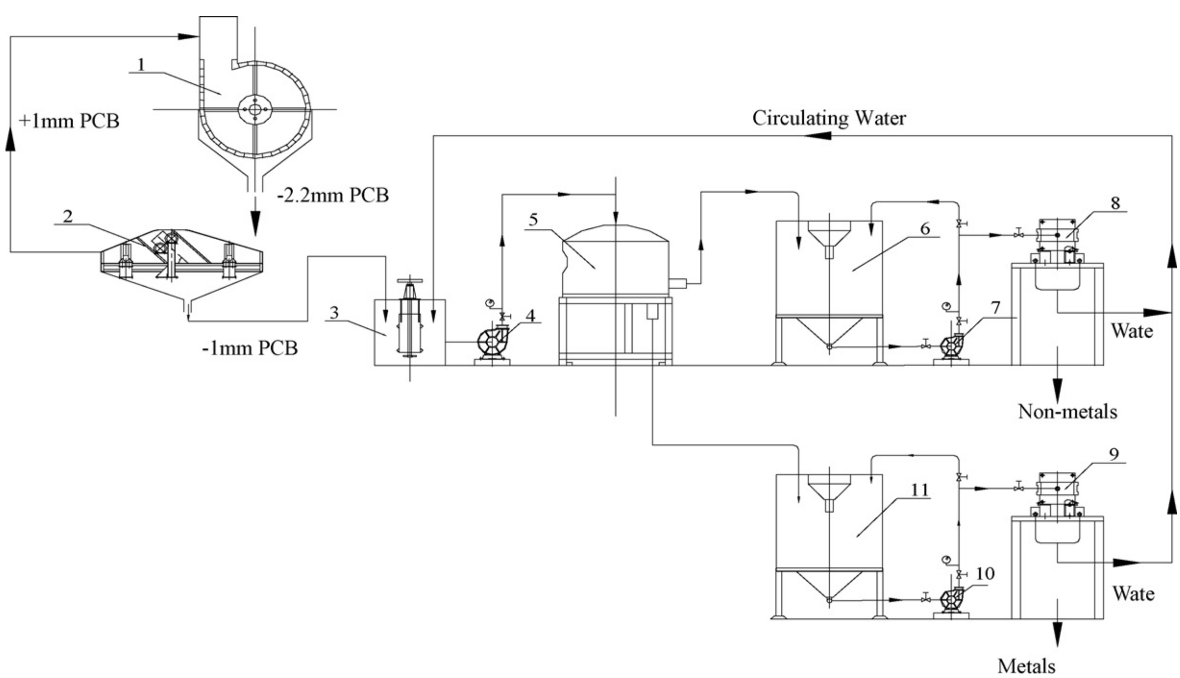

Fig. 5. A mechanical process of wet crushing-Falcon separation in water medium of recovery waste PCB. (1) Wet impacting crusher; (2) vibrating screen; (3) agitator; (4, 7 and 11) feeding pump; (5) Falcon separator; (8 and 9) pressure filter; (6 and 11) buffer.

the individual operating variables and their interaction terms on metal recovery using the Falcon separator. Sequential model sum of squares for the trials are shown in Table 3. The result shows that the linear model is suggested, and the quadratic model and the cubic model are aliased. The linear model summary statistics are shown in Table 4. "Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 6.199 indicates an adequate signal. This model can be used to navigate the design space.

The model equation, in units of the actual factors, for metal recovery is

$$\text{recovery} = +105.93500 - 79.81579 \times A - 0.10502 \times B - 0.16045 \times C$$

where A is the water pressure, MPa; B is the rotation frequency, Hz; C is the feed concentration, g/l.

Diagnostic statistics for the trials are shown in Table 5, which shows that the predicted value is close to the actual value. All assessment indicators of residual, leverage, student residual, cook's distance and outlier is come up to the required standard.

Our research has shown that effective crushing and separating of metal from discarded PCB could be done using wet impact crushing. The water medium could cool the machine and avoid dust and gas pollution. The water flow also helped discharge the crushed materials from the mill and to control over crushing. The Falcon centrifugal machine then recovered the useful components from materials sized less than 1 mm and solved the problem of separating minute particles. The grade of metal concentrate was up to 92.36% after one separation while the recovery was 97.12%. As a result, the processing technique shown in Fig. 5 was designed to use wet impact crushing and Falcon centrifugal machine concentration. Water was used in the process as the slurry medium: it could be recycled. This clean and non-polluting technique provides a new way to prevent the environmental pollution of waste PCB and to effectively recover valuable resources.

5. Conclusion

(1) When using a slippery hammerhead, a rotation speed of 1470 rpm, a water flow of 6 m^3/h and a sieve plate aperture of 2.2 mm, 95.87% of the crushed PCB had a particle size less than 1 mm. 94.30% of the metal was in this size range. When feeding −1 mm particles about 92.36% grade and 97.05% recovery was seen with a reverse water pressure of 0.05 MPa, the rotation speed transducer set at 30 Hz and the feed density of 20 g/l. A broader range of particle sizes could be separated using the Falcon separator with water medium. For recovery of metals from PCB the lower limit size for separation almost approaches zero.

(2) Compared to dry crushing techniques, wet impact crushing has the advantages of higher crushing efficiency, less over crushing and no secondary pollution. The main functions of water are (A) avoiding the diffusing of dust. (B) Avoiding excessive temperature in parts of the machine during the crushing process. (C) Avoiding gas production by pyrolysis during crushing. (D) Speeding up discharge of crushed material and controlling over-crushing in the process. The water can be recycled and only a small amount of fresh water need be supplied.

(3) In units of the factors, the linear model equation for recovery of metal was

$$\text{recovery} = +105.93500 - 79.81579 \times A - 0.10502 \times B - 0.16045 \times C$$

"Adequate Precision" of 6.199 of the linear model greater than 4 is desirable. Diagnostic statistics for the trials shows that the predicted value is close to the actual value, and all assessment indicators of residual, leverage, student residual, cook's distance and outlier is come up to the required standard.

(4) A new technique of "wet impact crushing followed by metal recovery using a Falcon separator in water medium" was provided.

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References

[1] J. Cui, E. Forssberg, Mechanical recycling of waste electric and electronic equipment: a review, J. Hazard. Mater. B 99 (2003) 243–263.

[2] H.M. Veit, A.M. Bernardes, J.Z. Ferreira, et al., Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy, J. Hazard. Mater. B 137 (2006) 1704–1709.

[3] J. Li, H.Z. Lu, S.S. L, et al., Optimizing the operating parameters of corona electrostatic separation for recycling waste scraped printed circuit boards by computer simulation of electric field, J. Hazard. Mater. 153 (2008) 269–275.

[4] Y.M. Zhao, X.F. Wen, B.B. Li, et al., Recovery of copper from waste printed circuit board, Miner. Metall. Process. J. 21 (2) (2004) 99–102.

[5] L. Zhou, Q.Z. Bai, J.H. Li, et al., Research on cryogenic comminution of discarded printed wiring boards, J. China Univ. Min. Technol. 35 (2) (2006) 220–224 (in Chinese).

[6] X.F. Wen, Y.M. Zhao, C.L. Duan, et al., Study on metals recovery from discarded printed circuit boards by physical methods, in: Proceedings of the 2005 IEEE International Symposium on Electronics & the Environment, New Orleans, LA USA, May 2005, pp. 121–128.