OPTIMIZATION OF PROCESS VARIABLES FOR FLOWING FILM CONCENTRATION OF GROUND PRINTED CIRCUIT BOARDS

A. Vidyadhar*, V.S. Vaishanau and A. Das
MNP Division, National Metallurgical Laboratory, Jamshedpur 831 007, India
* *ari@nmlindia.org*

ABSTRACT

Printed circuit boards, incorporated in most electrical and electronic equipment, contain valuable metals such as Cu, Ni, Au, Ag, Pd, Fe, Sn and Pb, etc. The circuit boards are rich in metal content and the need for processing these wastes to extract the metals values and remove the non-metallic constituents has been felt all over the world. It was evident from size-wise chemical analysis of the ground PCBs that the particulate system is quite rich in metal value with about 23% of the total powder being metallic. It contained 12.8% Cu, 2.4% Pb, 1.2% Sn, 2.5% Al and 0.5% Ni. This paper summarizes the effect of operating variables of crushed PCB waste using Wilfley Table. Detailed experimentation has been performed with crushed printed circuit boards according to a Box-Behnken design of experiments to establish the influence operating variables on the separation performance. The optimized conditions for maximizing the yield of the metal values with respect to the specified grade of the concentrate were discussed in the light of the experimental results.

Keywords: Printed circuit boards, Gravity Separation, Tabling, Electronic Waste, Metal recovery.

INTRODUCTION

Recycle and reuse of obsolete electronics has now been recognised as a big challenge. The printed circuit board is a major constituent of these obsolete and discarded electronic scraps. The typical constituents of PCB are non-metals (Plastics, epoxy resins, glass) >70%, Copper ~16%, solder ~4%, iron, ferrite ~3%, nickel ~2%, silver 0.05%, gold 0.03%, palladium 0.01%, others (bismuth, antimony, tantalum, etc.) <0.01% [1]. The purity of the precious metals in PCBs is more than 10 times that of rich-content minerals [2,3]. Therefore, the recycling of PCBs is an important subject, not only from the viewpoint of waste treatment, but also with respect to recovery of valuable materials [4,5]. Recently, Das et. al [6] developed a flowsheet using a combination of wet and dry processes to produce a rich concentrate with significantly high recoveries of metals from ground -0.5 mm PCB powder. Gravity separation is a useful technique to treat the pulverised e-waste in order to separate the metal values from the non-metallic gangue. Preliminary studies indicated that the gravity based separation can be adequately accomplished using flowing film concentration technique. The objective of the paper is to summarise the effect of operating variables, water flow rate, feed rate and inclination of the table, of crushed PCB while concentrating the particulate suspension using Wilfley Table.

MATERIALS AND CHARACTERIZATION METHODS

Raw Material

In the absence of a proper disposal, collection and sorting system of such wastes in India, identifying a source for the availability of waste printed circuit boards for carrying out research was quite difficult. 100 kg of waste PCB was procured from different sources. The undesirable attachments such as cords, frames and wires were removed from the PCBs manually. These boards were then cut into small (about 1.5 cm x 1.5 cm) pieces using manual and mechanical shear machines. These small pieces were then ground in a batch ball mill to a top size of 0.5 mm. The ball mill was intermittently stopped and the fines taken out by screening in order to prevent the generation of ultrafines. The ground PCB powder was used as the feed material for further characterization and processing studies.

Size Analysis

Ground PCB powder was subjected to physical separation in order to separate the metallic from non-metallic components. Powdered PCBs were subjected to size analyses and size wise chemical analyses. The PCB ground powder was analysed for size by dry sieving. The results of size analysis and distribution are shown in Table 1. It is observed from Table 1 that the ground material contained about 31% (by weight) material below 44 micron. About 25% of the materials were above 300-500 micron in size.

Liberation Studies

Microscopic liberation analysis using point count method was also performed to know the degree of liberation and interlocking status in each size class using optical microscope. The liberation data of the ground powder are also shown in Table 1. From this Table it is evident that the coarsest (300-500 micron) size class contains only about 8% (by number) interlocking of metallic and non-metallic constituents. For the finest size (-44 microns) it was not possible to observe liberation in the optical microscope. However, a glance at the liberation data of coarser size classes reveals that there should not be any interlocking in the finer size classes. In fact, all the metals and non-metals are completely liberated at 100 micron particle size.

Table 1. Size analysis and microscopic liberation data

Size (microns)	**Weight (%)**	**Liberation Analysis (Number %)**		
		Free Metal	**Interlocked**	**Free Gangue**
-500+300	24.27	20.08	7.87	72.05
-300+250	6.61	15.3	5.73	78.96
-250+150	18.18	13.6	3.75	82.65
-150+100	9.06	12.3	1.94	85.76
-100+75	2.92	9.37	0	90.62
-75+44	8.13	4.58	0	95.42
-44	30.83	-	-	-

Chemical Analysis

The composite sample and each of the size classes were analyzed for chemical composition in terms of significant metal values. The chemical analysis data are shown in Table 2. It may be seen from Table 2 that the ground PCB powder has about 23% total metal in it. This powder mainly contains 12.8% Cu, 2.4% Pb, 1.2% Sn, 2.5% Al and about 0.5% Ni. It is evident that the metal content decreased substantially with a decrease in particle size. The total metal content of the finest size class is less than 10% by weight. Interestingly, the composite sample contains about 12-13% copper in sharp contrast to the copper content of an ore which is about 0.7-1.0% in India. Due to low grindability of the metallic and non-metallic constituents of the PCBs, the generation of ultrafines could not be avoided. Based on the above characterization data and the large difference between the specific gravity values of the plastics and metals, gravity concentration was though of as the most effective method of separating the metals from the non-metallic constituents. In this work, gravity concentration by Wilfley Tabling was investigated from optimization point of view.

Table 2. Chemical analysis of the comminution product of PCBs

Size (microns)	**Cu (%)**	**Pb (%)**	**Sn (%)**	**Fe (%)**	**Al (%)**	**Ni (%)**	**Total Metal (%)**
Head Sample (analysed)	12.58	2.44	1.41	3.24	2.38	0.39	22.49
-500+300	23.45	2.67	1.81	5.73	2.01	0.96	36.64
-300+250	20.65	2.61	1.62	5.35	2.04	0.66	32.94
-250+150	16.79	2.69	1.48	4.65	1.99	0.54	28.14
-150+100	12.12	2.86	1.11	3.33	2.2	0.46	22.08
-100+75	9.4	2.89	1.24	3.23	2.01	0.31	19.08
-75+44	6.67	2.32	0.86	1.99	3.16	0.17	15.17
-44	2.58	1.74	0.68	1.14	3.12	0.11	9.41
Head (Calculated)	12.82	2.37	1.23	3.49	2.46	0.47	22.87

EXPERIMENTAL

Experimental Design

Processing of comminution fines of the e-waste was tried with a view to separate the metals from the nonmetallic constituents. The differences in specific gravity between metals and non-metals were exploited in flowing film concentration using Wilfley Tabling. In order to optimize the performance of the Wilfley Table a total of 15 experiments were performed according to the Box-Behnken design of experiment. The three operating variables were water flow rate (A), table inclination (B) and feed flow rate (C). The conditions for these experiments and the concentration response in the form of yield and grade are shown in the Table 3. The product samples were collected, dried and analyzed for total metal content (grade). These data are presented in Table 3.

Table 3. Box-behnken design of experiments for concentration using Wilfley Table

Expt. No.	**Water flow rate (lpm)**	**Inclination (degrees)**	**Feed rate (kg/hr)**	**Yield (%)**	**Grade (%)**
1	6.5	4	9	58.4	37.11
2	6.5	4	9	59.3	36.47
3	6.5	4	9	59	36.88
4	5	3	9	72.2	29.87
5	8	3	9	55.9	39.01
6	5	5	9	66.7	32.47
7	8	5	9	52.7	40.11
8	5	4	6	59.2	36.12
9	8	4	6	50.8	41.87
10	5	4	12	62.3	34.86
11	8	4	12	58.2	37.48
12	6.5	3	6	64.7	34.32
13	6.5	5	6	55.1	38.89
14	6.5	3	12	71.4	30.59
15	6.5	5	12	61.8	34.69

RESULTS AND DISCUSSION

The experimental data were fitted to a model. It was observed that a reduced cubic model fits the yield data well with a correlation coefficient (R^2) of 0.9973. The model expression for yield is given in Eqn. 1. Similarly, a reduced cubic polynomial described the grade data very well with an R^2 value of 0.9946 as shown in Eqn. 2. With the help of the model equations, optimization exercise was undertaken to maximize the yield at maximum possible grade. The optimum conditions were found out to be 7.02 lpm of water flow rate, 3 degrees inclination of the table and 6.11 kg/hr feed rate. At the optimum conditions, the yield is predicted to be 61.5% with a grade of 36.1%. Thus, it is established that the feed material with 23% metals may be enriched to 36% metal in one single pass in a Wilfley Table at nearly 62% yield.

In terms of coded factors A, B & C, the equations are:

$$\text{Yield} = 58.90 - 3.13\,A - 4.80\,B + 2.99\,C + 0.58\,AB + 1.08\,AC - 1.32\,A^2 + 4.3\,B^2 + 0.050\,C^2 + 2.62\,A^2B - 4.45\,AB^2 \qquad \text{Eq (1)}$$

$$\text{Grade} = 36.82 + 2.09\,A + 2.17\,B - 1.7\,C - 0.37\,AB - 0.78\,AC - 0.12\,BC + 0.75\,A^2 - 2.21\,B^2 + 0.01\,C^2 - 1.24\,A^2B + 2.10\,AB^2 \qquad \text{Eq (2)}$$

Where, A, B and C corresponds to water flow rate, inclination of the table and feed rate, respectively, varying from – 1 to + 1. In actual, for A, – 1 corresponds to 5 lpm and + 1 corresponds 8 lpm. For B, – 1 corresponds to 3 degree and + 1 corresponds to 5 degree. For C, – 1 corresponds to 6 kg/hr and + 1 corresponds to 12 kg/hr.

Figs. 1-3 show the response surfaces which were generated from the experimental data. Fig. 1 is plotted for the optimum condition of feed rate, 6.02 kg/hr. The maximum yield is obtained at low inclination and low water flow rate. The yield is observed to increase with a decrease in water flow rate.

At the optimum condition of water flow rate of 7.02 lpm the response surface is shown in Fig. 2. The maximum yield is obtained at high feed rate and low inclination. The yield is observed to increase with an increase in feed rate. The yield drops with an increase in table inclination and also with a decrease in feed rate.

Figure 3 is generated at 3 degree inclination of the table. The grade of the concentrate increases with a decrease in feed rate almost linearly. However, the grade rises sharply as the water flow rate increases.

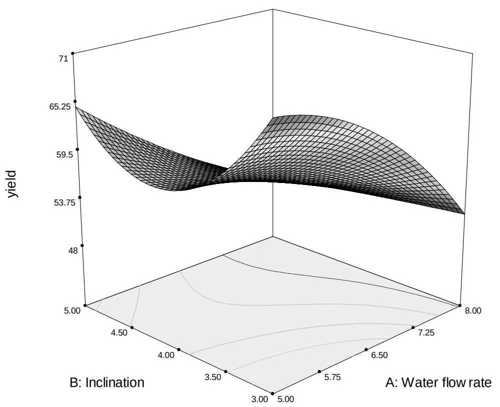

Figure 1. Response surface at 6.02 kg/hr feed rate

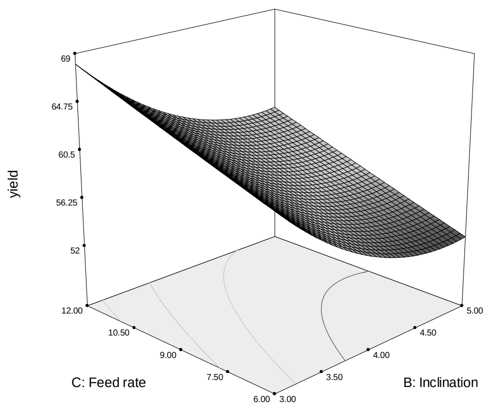

Figure 2. Response surface at 7.02 lpm water flow rate

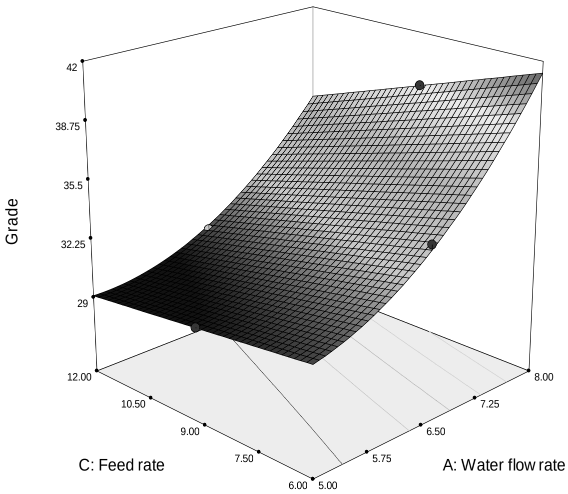

Figure 3. Response surface for grade at 3.00 degree inclination

CONCLUSIONS

This paper summarizes the effect of operating variables on concentration of crushed PCBs using Wilfley table. The optimum conditions were found out to be 7.02 lpm of water flow rate, 3 degrees inclination of the table and 6.11 kg/hr feed rate. At the optimum conditions, the yield is predicted to be 61.5% with a grade of 36.1%. It was established that the feed material with 23% metals may be enriched to 36% metal in one single pass in a Wilfley Table. The yield increases with increase in feed rate, decrease in table inclination and decrease in water flow rate. However, the effect of these variables on the grade of the concentrate is found to be the reverse. Hence, there is a compromise required depending upon the requirement.

ACKNOWLEDGEMENTS

The financial support from Ministry of Environment and Forests (MoEF) is gratefully acknowledged.

REFERENCES

1. M. Goosey and R. Kellner. *Circuit World* 2003, Vol. 29 (3), pp. 33-37.
2. T. Lehner: in Proc. of the IEEE International Symposium on Electronics and the Environment, 1998, pp. 42-47.
3. W. He, G. Li, X. Ma, H. Wang, J. Huang, M. Xu and C. Huang. *J. Hazard.Mater.* 2006, Vol. B 136, pp. 502-512.
4. W.J. Hall and P.T. Williams. *Resour. Conserv. Recycl.* 2007, Vol. 51, pp. 691-709.
5. H.M. Viet, A.M. Bernardes, Ferreira, J.A.S. Tenorio and C.F. Malfatti. *J. Hazard.Mater.* 2006, Vol. B 137, pp. 1704-1709.
6. A. Das, A. Vidyadhar and S.P. Mehrotra. *Resour. Conserv. Recycl.* 2009, Vol. 53, pp. 464-469.