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The application of pneumatic jigging in the recovery of metallic fraction from shredded printed wiring boards

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Abstract

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams worldwide with volumes increasing by 40% each year. WEEE has attracted increasing concern worldwide due to its high metal content and the potential environmental threat which results from uncontrolled recycling practices. Innovative physical separation techniques for WEEE recycling are preferential compared with chemical methods because of the reduction of energy and chemical consumption as well as potential environmental threats. Pneumatic jigging is a dry separation process capable of achieving good separation of coarse material within a very narrow density range, which makes it suitable as a pretreatment process for WEEE recycling. The work presented in this paper investigates the potential application of pneumatic jigging in metal recovery from WEEE. A pilot scale pneumatic jig has been developed by University of Nottingham Ningbo to separate shredded printed wiring boards into two streams: a light fraction (mainly non-metallic fraction consisting of glass fiber, fluffs, and plastic pieces) and dense fraction (metallic fraction). The novelty of work presented in this paper is the application of a dry separation technique in WEEE recycling for metal recovery. Compared with conventional wet separation processes involved in WEEE recycling industry, dry separation has the advantage of zero secondary pollution. The results of this experimental program show pneumatic jigging to be an effective and environmental friendly technique as a pretreatment process for the recovery of the metallic fraction from shredded WEEE.

Keywords
WEEE, pneumatic separation, jigging, printed wiring board, metal recycling

Introduction

The evolution of information technology in the 21st century made significant contribution to the productivity and economic growth worldwide as well as a series of environmental problems. With the rapid upgrade of electronic products, waste electrical and electronic equipment (WEEE) has become one of the most rapidly growing waste streams (Herat and Agamuthu, 2012). Global WEEE production is expected to increase from 41.5 million tons in 2011 to 93.5 million tons in 2016, with a compound average growth rate of 17.6% (Marketsandmarkets.com, 2011). In terms of revenue, the WEEE market is estimated to rise from \$9.15 billion in 2011 to \$20.25 billion in 2016 at a compound average growth rate of 17.22% (Marketsandmarkets.com, 2011). From resource and economic points of view, WEEE can be regarded as an “urban mine” for metal extraction. A lifecycle assessment report for metal recovery from high-grade WEEE stated the recovery of 165 kg copper and precious metal, 381 kg iron, and 22 kg aluminum from 1000 kg of high-grade WEEE (Bigum et al., 2012). The high precious metal content is the major factor that drives the WEEE recycling market worldwide. The WEEE issue is particularly important to China. Although there are international organizations like the Basel Convention trying to ban cross-boundary transportation of WEEE, China is still the destination of more than 70% of WEEE produced around the globe (He et al., 2008). Most WEEE recycling in China is conducted by informal sectors with little concern about environmental impact and health and safety issues. The commonly adopted recycling process for WEEE recycling includes manual dismantling, open burning, de-soldering, acid leaching, and open dumping (Schluep et al., 2009). The operation of these illegal sectors releases large amounts of heavy metal and toxic organic pollutants to the surrounding environment and generates health threats to their employees and people living in the local

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areas (Song and Li, 2015). It is reported that in 2007 over 700,000 people were employed in the WEEE recycling industry in China, among which 98% worked for informal sectors (Yu et al., 2009). One of the most famous examples of WEEE-induced environmental and human health problems is that at Guiyu, Guangzhou. An illegal WEEE recycling operation has been active for over 10 years (Wong et al., 2007). Elevated heavy metal content has been reported in air, river, sediment, and soil in the surrounding area (Wong et al., 2007). Lead, nickel, and cadmium concentrations in local residents' body tissues are found to be significant higher compared with other places (Song and Li, 2015). In addition to heavy metal contamination, the presence of brominated flame retardants in printed wiring board (PWB) also leads to the release of organohalogens during the open incineration process (Labunska et al., 2015; Li et al., 2014). Nephroliths and some respiratory problems became common local diseases and no potable water could be found within 10 km of this town (Lai and Lu, 2003).

Formal WEEE recycling operations with environmental friendly techniques provide a solution to the environmental impact and health and safety problems. Currently, the majority of physical processing for WEEE recycling relies on wet density-based separation with only a 60–70% metal recovery rate. In addition, the wet separation process generates secondary wastewater with high metal content (He and Xu, 2014). Various national level regulations have been issued to control WEEE problems over the past few years, for example Directive 2012/19/EU on WEEE in the European Union and Regulations on the Prevention and Control of Environmental Pollution by WEEE in China, etc. However, the complexity of material and structure of WEEE creates substantial challenges for the recycling industry, especially of PWBs. Conventional PWB recycling technologies include chemical methods like hydrometallurgy methods (Bas et al., 2014; Tuncuk et al., 2012; Yazici and Deveci, 2014), pyrolysis (Hall and Williams, 2007), supercritical water treatment (Xiu et al., 2013), and bioleaching processes (Brandl et al., 2001, Marhual et al., 2008), as well as some physical methods like magnetic and electrostatic separation (Marhual et al., 2008, Senouci et al., 2013) and air classification (Marhual et al., 2008). Chemical methods have the advantage of better efficiency for metal recovery; on the other hand, mechanical pretreatment practices have the potential to improve the environmental performance of the overall process due to their chemical-free nature. Therefore an integrated system with both mechanical and chemical technologies is required for the recycling of WEEE (He and Xu, 2014). The dry separation method is the preferential process compared with wet separation techniques for physical pretreatment process because of no secondary pollution. The work presented in this paper investigates the potential application of pneumatic jigging as a pretreatment procedure for metal recovery from PWBs.

Jigging

Jigging is one of the oldest gravity concentration techniques. It separates materials based on specific gravity by the pulsation of fluid through a bed of materials (Perry et al., 1997). Jigging can be classified into two categories based on the fluid employed in the system: pneumatic jigging using air to produce pulsation and wet jigging using a liquid.

Separation mechanism of jigging

Research has been carried out to explain the separation mechanism of jigging. Various theories have been proposed, e.g. the energy dissipation theory (Rong and Lyman, 1993) and potential energy theory (Tavares and King, 1995). However, the separation mechanism of jigging is not clearly understood. The general behavior of particles can be explained by single particle theory, whose principle lies in Stokes' law and terminal velocity (Gupta and Yan, 2006). There are essentially three forces acting on a particle in the jigging action: gravitation, buoyance, and drag forces (Shinde, 2014). The motion of a single particle can be described by

$$M_s a_p = F_g - F_b - F_d \tag{1}$$

where M_s is the mass of solid, a_p the particle acceleration, and F_g, F_b, F_d are the gravitation, buoyance, and drag forces, respectively.

The separation of different materials is governed by their settling rate. Equations (2) and (3) describe the terminal settling velocity of solid spheres in a fluid.

For fine particles with viscous resistance (Stokes' law):

$$v_{T,fine} = \frac{g\left(\rho_s - \rho_f\right)d^2}{18\mu} \tag{2}$$

For coarse particles with turbulent resistance (Newton's law):

$$v_{T,coarse} = \sqrt{\frac{4g\left(\rho_s - \rho_f\right)d}{3C_D\rho_f}} \tag{3}$$

where $v_{T,fine}; v_{T,coarse}$ are terminal settling velocities, d is the particle diameter, ρ_s the density of solid, ρ_f the density of fluid, C_D the drag coefficient, μ the fluid viscosity, and g the gravitational acceleration.

The separation of particles in jigging results from the repeated expansion and contraction induced by pulsation of fluid, air in this case to avoid secondary contamination problem from wet separation methods. The behavior of heavy and light particles is illustrated in Figure 1.

Each cyclic jigging action comprises four steps (Shinde, 2014):

A: Bed at rest: particle mixtures at rest on the screen;

B: Pulsation: air pulsation forced through particle bed from the bottom, particles being lift up by air, and this is a density based differential acceleration separation process;

C: Hindered settling: after air pulsation, particles start to settle, drag force dominate the separation of particles based on density and size, the key mechanisms is hindered settling;

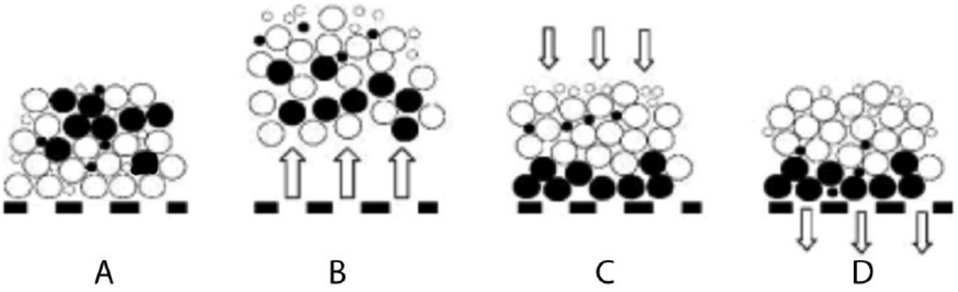

Figure 1. Expansion and contraction of a bed of particles due to jigging action (black particles indicate heavy material and white particles indicate light material; adapted from Gupta and Yan, 2006).

D: Consolidation trickling: final stage of jigging action, compaction of particle bed, fine particles penetrate through dense coarse particles into the bottom layer, this is particle size dependent separation process.

The separation efficiency of pneumatic jigging is controlled by four major process parameters (Rong and Lyman, 1991):

- Jigging time: there is a linear relationship between the degrees of particle stratification and jigging time, elongated jigging time can promote particle separation efficiency.
- Superficial air velocity: the differential acceleration and hindered settling process is governed by the superficial velocity of pulsation fluid, which determines the drag force applied on particles (Mukherjee and Mishra, 2006).
- Frequency of pulsation: the frequency of pulsation should enable enough expansion and compaction time for individual jigging actions therefore particle mixing generated from turbulence could be minimized.
- Feed characteristics: including size ratio, volume fraction and particle bed, these factors determines whether particle mixture can be separated or not.

Application of jigging technology

Most of applications of jigging are for coal and other minerals processing. Examples for pneumatic jigging application include removal of sulfur and ash content in coal (Boylu et al., 2014; Panda et al., 2012; Sampaio et al., 2008; Singh and Das, 2013) and separation of dry fine coal particles from non-aqueous gangue particles (Luo et al., 2008). Fluid used in wet jig provides higher viscosity compared with air, which enables ore concentration applications (Beniuk et al., 1994; Naudé et al., 2013). To avoid the generation of contaminated fluid from wet separation processes, dry jigging is the preferential choice in waste management applications. The development of jigging applications in waste management is driven by their economic and environmental performance. One of the most successful applications is the recycling of construction and demolition waste with pneumatic jigging. Recycled aggregate produced from pneumatic jigging separation proves to be a good quality substitute for natural aggregates in pavement sub-base materials (Cazacliu et al., 2014). The potential applications of wet jigging for the separation of non-ferrous car scrap (De Jong and Dalmijn, 1997) and waste plastics (Ito et al., 2010; Tsunekawa et al., 2005) have also been reported. To assess the potential of pneumatic jigging as a dry separation process for WEEE recycling, a batch-scale pneumatic jig has been developed by the University of Nottingham, Ningbo. A trial with WEEE samples provided by Axion Recycling has been performed (Bennett et al., 2009). Batch operation generates metal-rich product; to be of practical and commercial relevance a continuous pneumatic jig has been developed.

Experimental details

Pilot scale pneumatic jigging system

The novel pilot scale pneumatic jigging system used in this experiment consists of four main units: feeding unit, air supply unit, separation chambers, and discharge unit (Figure 2). A vibratory feeder has been employed to load samples into the separation chamber at constant rate. Air pulsation for separation is provided by a 4 kW blower (Secomak, CL 20/01), which is controlled with frequency converter. The superficial velocity can be adjusted between 0 and 8 m/s. Air from the blower split into two streams for two separation chambers. The air supply is controlled by a pair of pneumatic butterfly valves with programmable logic control to operate in alternating pattern. Air duct from the blower is connected to the separation chambers through air distribution system which enhance the uniformity of air distribution within separation chamber. This pneumatic jigging has two Perspex separation chambers with the same dimension (length × width × height = 170 mm × 170 mm × 300 mm). The bottom screen used is standard staggered 60° pattern perforated plates with 3 mm diameter holes. The movement of particles within the separation chamber is driven by a pair of vibrators (Invicta Vibrators, BLZ/05-2/4) attached to both sides of the frame. The vibration intensity of the vibrators can be adjusted from 0 to 100% of its full vibration capacity. The top fraction exits the separation chamber from the top outlet under vibration. The extraction of bottom fractions is assisted with a rotary valve (Rotolok Valve, Round 150).

Sample preparation

The sample used in this experiment is computer mother boards disassembled from waste computers collected by the recycler from households and internet cafés (lithium batteries removed).

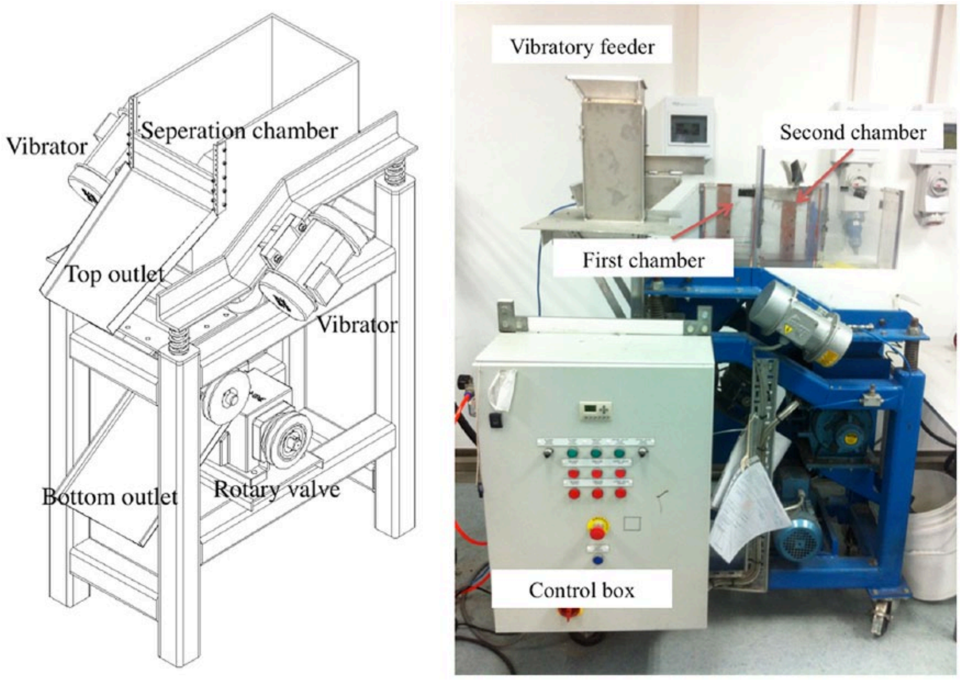

Figure 2. Pilot scale pneumatic jigging developed by University of Nottingham (design drawing provided by Tony Gospel).

Computer main boards of different brands are included in the sample, including ASUS, APON, AsRock, Colorful, Dell, ECS, Foxconn, Gemen, Gigabyte, HASEE, Hummer, Intel, IWILL, Koloe, MSI, ONDA, SOLTEK, SOYO, etc., which are widely available on the market and represent the miscellaneous nature of the waste stream. The computer main boards were shredded with a CSF570 hammer mill from Fengli Pulverization Equipment Co., Ltd; aperture size on the discharge plate is 10 mm. Aluminum heat sinks have been manually removed from each waste computer main boards prior to shredding to avoid any jamming during the grinding process.

Shredded PWBs have quite a wide size range, so particles size analysis was carried out with a Capco Inclyno test sieve shaker. Sieves used for particle size distribution analysis are Endecotts sieves, which have a square root of two ratio for aperture widths of adjacent sieves. The particle size distribution of a shredded PWB is shown in Figure 3. The density of the shredded PWB sample is 2.27 g cm^{-3}.

Operation parameters

Both batch and continuous pneumatic jigging separation has been investigated. The sample was loaded into the separation chambers prior to operation. The air pulsation was then started with the blower to establish stratification of light and dense fraction layers. The movement of particles in the separation chamber is generated by vibration of the separation chamber. To establish continuous operation, the vibrators, feeder, and rotatory valve are started and the stratified layers will exit the outlets, respectively. Initially, batch scale operation has been conducted to establish basic operation parameters like bed height and superficial air velocity. There is no continuous airflow within the design of this pneumatic jig to suspend fine particles; therefore, two layers of steel mesh with pore size of 150 μm have been placed on top of the supporting screen to prevent fine particles from penetrating into the ducts for air supply. The steel mesh is also used to cover the top of both separation chambers to confine the movement of particles during jigging actions. The particle bed height is determined by superficial velocity and the height of separation chamber. Fluidization of particles should be achieved with air pulsation and the bed expansion should be contained within the separation chamber. A dust extraction unit (Donaldson, Easy Trunk) has been used to collect particles blown out of the chambers by pulsed air. Batch scale experiments with different combinations of air superficial velocities and bed heights demonstrate that a suitable bed height is 8–10 cm with a superficial velocity of air pulsation between 3.6 m s^{-1} and 4.0 m s^{-1} for the pilot jig. The duration of each air pulsation is 1 s; therefore, the frequency is 1 Hz. With the operation parameters stated above, the jigging time should be greater than 2 min to achieve stratification of two distinguishable layers – the top layer consists of mainly non-metallic fraction and the bottom layer consists of metallic particles and non-liberated parts. For all continuous separation experiments, the process starts with 2 min of batch operation to establish the stratification condition. With superficial velocity and other jigging operation parameter established from batch experiment, two sets of operation parameters (conditions 1 and 2) have been identified for continuous separation. The height and size of outlets for both conditions are exactly the same. A pair of 50 mm height Perspex plates serves as a weir between chambers, which determines the height and size of outlets for bottom and top streams in the pneumatic

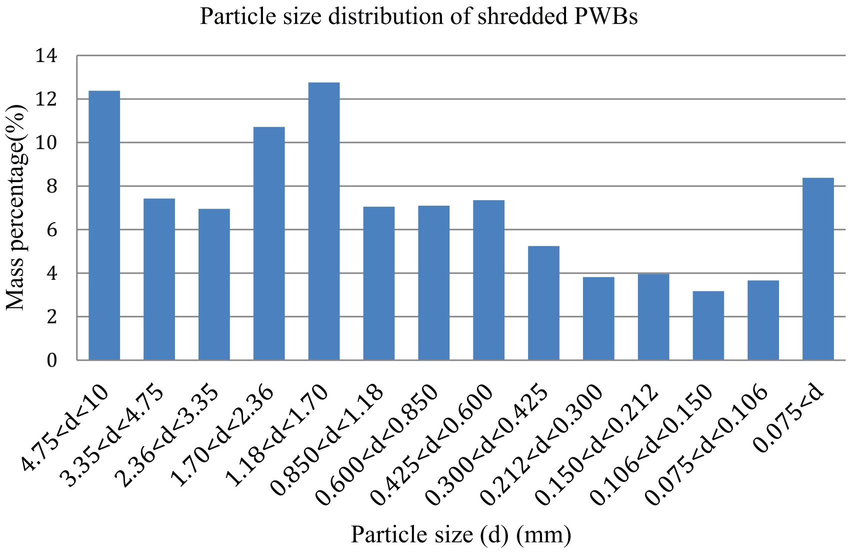

Figure 3. Particle size distribution of shredded PWB from a hammer mill.

jigging. The sizes of outlet for bottom fraction on the first and second chambers are 20 mm and 15 mm, respectively. The sizes of outlet for the top fractions are kept at 50 mm because fluffs and fibrous material tend to form agglomerates. The corresponding vibration intensities for conditions 1 and 2 are 30% and 25% of full capacity of the vibrators. The difference in vibration intensities results in different retention time of particles within the separation cell.

Method for product analysis

Riffle was used to acquire representative samples from the separation process. An Ultrapyc 1200e gas pycnometer was used to measure the true density of samples, which provides qualitative indication of the extent of separation. The metal content of each sample fraction is analyzed to provide quantitative information of the separation efficiency. A representative sample of each fraction is grinded with a Retsch SM2000 cutting mill followed by a Retsch ZM 200 centrifugal mill. The particle size of the sample is reduced to below 250 μm to ensure the uniformity of sample in the following microwave digestion stage. A CEM Mars 5 microwave digester is then used to dissolve the sample. Elementary analysis is conducted with ThermoFisherM Series iCE 3500 atomic absorption spectrometry and PerkinElmer NexION 300x inductively coupled plasma–mass spectrometry.

Results and discussion

Figure 4 shows an image of representative samples from the pneumatic separation process. Before separation, the shredded PWB is a mixture of particles and fibrous materials. Pneumatic jigging separates the shredded particles into two streams: the bottom fraction comprises plastic particles, PWB fragments, and metallic parts, and the top fraction is mainly a mixture of fibers, fluff, and small PWB pieces. The sample recovered from the dust extraction unit is essentially an aggregation of fluff and fibrous material with fine particles trapped inside.

The identification of boundary layer between top fraction and bottom fraction is based on visual observation. For batch scale separation, the sample is extracted from the separation chamber with a vacuum cleaner to prevent re-mixing. In the continuous separation process, separation of top and bottom layers is achieved by adjusting the height and size of the outlets of separation chambers. Experimental records of three runs for both batch and continuous separation are presented in the tables below. Table 1 shows the results from batch operation with a retention time of 4 min. Table 2 illustrates two different conditions of continuous separation with top to bottom fraction weight ratio of about 1:6 and 1:9, for which the throughput is 170 kg hr^{-1} and 150 kg hr^{-1}, respectively.

Table 1 shows considerable variation in weight ratio between each run. This is caused by the relatively small sample size and the manual extraction process. Compared with batch operation, the results from continuous operation demonstrate good consistency for both weight and density measurement. The density change for top and bottom fractions indicates concentration of metallic fractions in the bottom fractions. Further chemical analysis has been carried out to determine the efficiency of this pneumatic separation process.

Table 3 shows different metal concentrations in representative samples of the continuous pneumatic separation process. The hammer mill used for grinding is made of steel; therefore, the iron concentration may be affected. The metal concentration of shredded PWB before separation is 34.6%. For condition 1, metal contents in the bottom and top fraction are 15.3% and 39.9%, respectively. For condition 2, the corresponding metal contents in the bottom and top fraction are 14.0% and 45.1%. The metal concentration efficiency in condition 2 is higher than that of condition 1, which results from its longer retention time in the jig. Pneumatic jigging proves to be an effective technology for

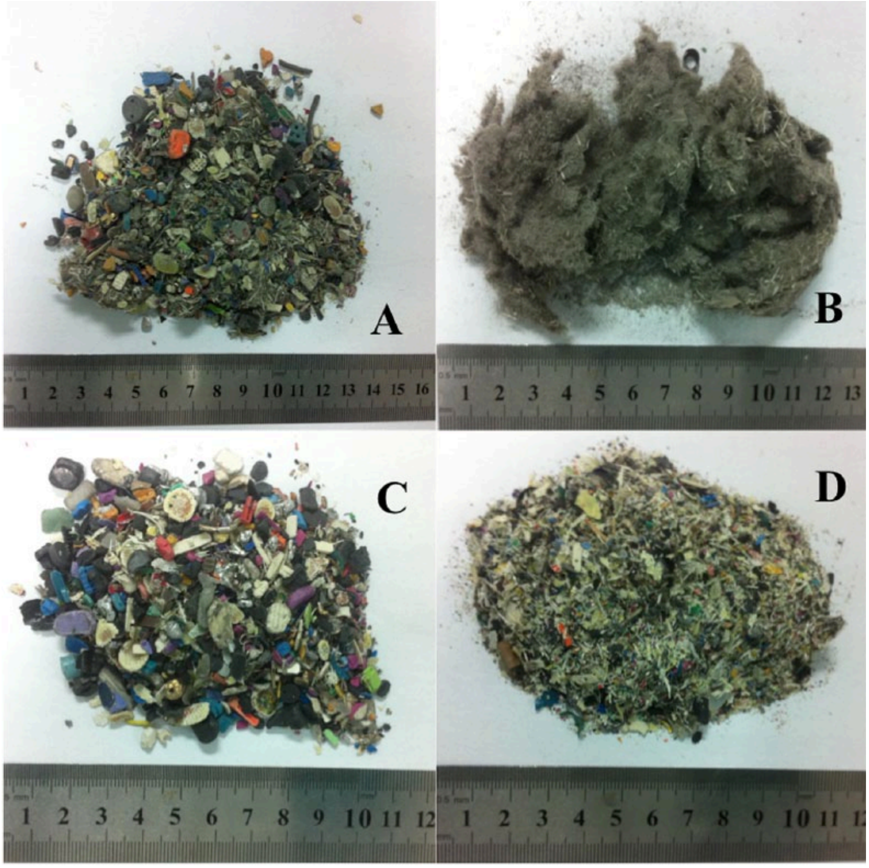

Figure 4. PWB samples from pneumatic jigging: (a) shredded PWB before separation; (b) dust collected in the dust extraction unit; (c) bottom fraction; (d) top fraction.

Table 1. Batch pneumatic separation results of shredded PWB.

Run	1st chamber			2nd chamber		
	Top	Bottom	Ratio	Top	Bottom	Ratio
Weight of sample (kg)						
1	0.19	1.98	10.42	0.16	3.16	19.75
2	0.22	2.80	12.73	0.22	1.96	8.91
3	0.25	2.93	11.72	0.26	1.88	7.23
Average	0.22	2.57	11.62	0.21	2.33	11.96
RSD[a]	11%	16%	8%	20%	25%	46%
Density (g cm^{-3})						
1	2.04	2.59	1.27	2.06	2.29	1.11
2	1.94	2.52	1.29	1.94	2.66	1.37
3	1.93	2.54	1.32	1.92	2.42	1.26
Average	1.97	2.55	1.3	1.97	2.46	1.25
RSD[a]	2.5%	1.2%	1.6%	3.1%	6.2%	8.5%

[a] RSD = relative standard deviation.

the recovery of metallic fractions from shredded PWB. Most of the metals concentrate in the bottom fractions, although some metals such as lithium concentrate in the top fraction. The results also show high concentration of various elements in the sample recovered from the dust extraction unit, e.g. barium (3.4 times that of original sample), titanium, and palladium. The weight of sample collected from the dust extraction unit accounts for 0.51% of the total weight of processed PWB; therefore, the loss is minor from a recycling point of view.

Conclusions and future work

The work presented in this paper, which is original and unprecedented, has demonstrated the feasibility of applying dry

Table 2. Continuous pneumatic separation results of shredded PWB.

Condition 1				Condition 2			
Weight of sample (kg)				Weight of sample (kg)			
Run	Top	Bottom	Ratio	Run	Top	Bottom	Ratio
1	3.70	21.65	5.85	1	2.25	20.88	9.28
2	3.83	21.80	5.69	2	2.13	19.91	9.35
3	3.68	20.68	5.62	3	2.37	21.10	8.9
Average	3.74	21.38	5.72	Average	2.25	20.63	9.18
RSD	1.8%	2.3%	1.7%	RSD	4.4%	2.5%	2.2%
Density (g cm^{-3})				Density (g cm^{-3})			
Run	Top	Bottom	Ratio	Run	Top	Bottom	Ratio
1	1.85	2.55	1.38	1	1.95	2.34	1.2
2	1.89	2.61	1.38	2	1.98	2.34	1.19
3	1.89	2.60	1.38	3	1.95	2.32	1.19
Average	1.88	2.59	1.38	Average	1.96	2.34	1.19
RSD	1.0%	1.0%	0.0%	RSD	0.7%	0.4%	0.4%

Table 3. Metal concentration in pneumatic separation samples.

Element	Unit	A	B	C	D	E	F
Cu	%	21.3	9.9	25.0	8.5	29.3	6.5
Fe	%	5.2	1.4	5.6	1.2	6.7	11.9
Ni	%	0.5	0.1	0.5	0.1	0.6	0.4
Al	%	2.2	2.8	2.1	3.1	1.7	2.3
Pb	%	1.7	0.2	2.3	0.1	2.2	1.4
Sn	%	1.3	0.1	1.7	0.1	1.7	1.2
Zn	%	1.1	0.1	1.4	0.1	1.4	1.0
Cr	ppm	3940.8	320.9	6491.8	582.5	8300.3	58.0
Ba	ppm	3499.7	1761.0	1375.6	2049.7	1757.2	11757.8
Sb	ppm	2804.1	2694.0	3015.4	2758.3	3140.5	2903.2
B	ppm	1096.7	1491.8	613.3	1475.2	802.6	1289.7
Ti	ppm	505.4	204.6	406.9	224.1	432.3	1116.8
Ga	ppm	468.9	230.3	172.1	260.1	222.5	1181.2
Zr	ppm	174.3	18.5	80.5	23.8	75.3	629.8
Sr	ppm	133.6	184.4	92.6	181.6	114.4	119.1
Mn	ppm	444.4	105.6	569.9	171.9	657.2	769.4
Co	ppm	8.7	4.7	11.5	6.6	12.8	28.8
Au	ppm	46.9	32.5	11.9	32.5	7.5	65.4
Bi	ppm	12.9	7.5	8.9	6.4	7.6	47.8
Cd	ppm	16.0	20.7	7.0	17.8	13.7	56.6
Li	ppm	5.8	9.9	2.9	12.1	4.1	6.6
Hf	ppm	5.0	0.6	2.3	0.8	4.6	16.2
Ce	ppm	4.9	7.3	2.7	6.8	3.4	32.3
Pd	ppm	4.2	0.9	4.0	1.0	4.5	8.9
Hg	ppm	0.1	0.1	0.1	0.2	0.2	0.1
Pt	ppb	21.3	5.9	15.4	6.8	21.1	32.7
Ta	ppb	9.8	2.3	12.1	4.2	10.9	3.2

A: shredded PWB before separation; B: top fraction from condition 1; C: bottom fraction from condition 1; D: top fraction from condition 2; E: bottom fraction form condition 2; F: sample from dust extraction unit.

separation techniques, i.e. pneumatic separation, in metal recovery from WEEE. This provides a potential pretreatment process to improve the overall economic and environmental performance of WEEE recycling. Two continuous operation conditions have been identified with light-to-dense fraction weight ratio of 1:5.7 and 1:9.2. In terms of metal concentration, total metal content in the dense fraction from condition 2 has been increased to 45.1% from 34.6% in shredded PWB.

Removal of certain mass fractions at an early stage of shredding could reduce the energy consumption of the shredding process. The pneumatic jig's capability for processing coarse particles makes it suitable as a pretreatment process to improve the overall economic and environmental performance of recycling. The subsequent recovery process could be re-shred the dense fractions produced by pneumatic jig for better liberation and concentrate with techniques like vibratory separation (Habib et al., 2013). The results reveals high concentrations of boron (B), strontium (Sr), gold (Au), cadmium (Cd), and cerium (Ce) in the top fraction. This is because these metals, which exist as thin films or a layer of deposits in PWBs, become trapped in the fluff and fibrous material during handling. The shredding mechanisms need to be reappraised to reduce the loss of precious metals. The following work will be carried out to improve performance of pneumatic separation of WEEE:

- Due to the complex and heterogeneous nature of PWBs, multi-stage separation under different operation conditions could be adopted to improve the separation efficiency.
- Particle size could be reduced to increase liberation of metals from non-metallic fractions.
- The retention time of sample within the pneumatic jigging could be increased to enhance the concentration effect.
- A filter could be installed on the top of separation chamber to prevent loss of valuable metals in fine particles.

Declaration of conflicting interests

The authors declare that there are no conflicts of interest.

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