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Electronic Waste Disassembly with Industrial Waste Heat

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ABSTRACT: Waste printed circuit boards (WPCBs) are resource-rich but hazardous, demanding innovative strategies for post-consumer collection, recycling, and mining for economically precious constituents. A novel technology for disassembling electronic components from WPCBs is proposed, using hot air to melt solders and to separate the components and base boards. An automatic heated-air disassembling equipment was designed to operate at a heating source temperature at a maximum of 260 °C and an inlet pressure of 0.5 MPa. A total of 13 individual WPCBs were subjected to disassembling tests at different preheat temperatures in increments of 20 °C between 80 and 160 °C, heating source temperatures ranging from 220 to 300 °C in increments of 20 °C, and incubation periods of 1, 2, 4, 6, or 8 min. For each experimental treatment, the disassembly efficiency was calculated as the ratio of electronic components released from the board to the total number of its original components. The optimal preheat temperature, heating source temperature, and incubation period to disassemble intact components were 120 °C, 260 °C, and 2 min, respectively. The disassembly rate of small surface mount components (side length ≤ 3 mm) was 40–50% lower than that of other surface mount components and pin through hole components. On the basis of these results, a reproducible and sustainable industrial ecological protocol using steam produced by industrial exhaust heat coupled to electronic-waste recycling is proposed, providing an efficient, promising, and green method for both electronic component recovery and industrial exhaust heat reutilization.

INTRODUCTION

A printed circuit board (PCB) mounted with electronic components (ECs) is the centerpiece of all electric and electronic equipment (EEE). The rapidity of technological innovation driven by demands for increasingly high data processing speed has led to rapid obsolescence of PCB assemblies (PCBAs), causing the global problem of accumulating electronic waste (e-waste).^{1,2} Waste PCBAs (WPCBAs) are resource-rich but hazardous to human health and the environment. Approximately, one-third of the weight of WPCBAs consists of metals, mainly Cu, Sn, Fe, and Pb. In addition, precious metals, such as Au, Ag, and Pd, which were used as contact materials or plating layers because of their electric conductivity and chemical stability,³ are 10 times more abundant in e-waste than in natural ores.⁴ This has led to the proliferation of artisanal e-waste mining in unregulated cottage industries, especially in developing countries. Such artisanal mining processes contribute to the exposure of workers, nearby residents, and ecosystems to toxic metals and halogenated flame retardant chemicals, with devastating consequences to health and environmental quality.^{2,5,6}

Many studies based on pyrometallurgy,^{7–10} hydrometallurgy,^{11–13} biometallurgy,^{14,15} supercritical fluid,^{16,17} and mechanical–physical processes,^{18,19} mainly aiming at metal recovery,^{20,21} have been conducted to identify cost-effective and environmentally sustainable ways of recycling WPCBs. However, these studies focus on bare boards not mounted with ECs, which does not represent the real scenario of discarded WPCBAs that typically contain capacitors, relays, resistors, and integrated circuits. Although WPCBAs are designed for durability up to 500 000 h, the average end-of-life for ECs is 20 000 h, less than 5% of its designed lifespan.^{20,21} Hence, many components are still functional and usable at the time of disposal as e-waste. Therefore, disassembling ECs from WPCBs is a crucial step in the WPCBAs recycling chain to conserve scarce resources, reuse functioning ECs, and eliminate potential exposure to hazardous materials.^{2,22,23}

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Figure 1. WPCBAs.

Developing sustainable technology for WPCBAs disassembly is urgent, particularly in the developing countries in Asia and Africa,

where unregulated recyclers use artisanal tools to separate ECs by simply heating WPCBAs on a coal-heated plate to melt solders. Serious environment pollution and severe exposure to toxic chemicals result from these crude practices.^{2,10,24,25} In response to the adverse impacts of artisanal e-waste mining, China outlawed such practices in 2011.²⁵ Automated e-waste recycling approaches have been developed in Japan and Germany.^{26,27} However, because of the large-scale nature of such processes, their complexity and economic costs of such recycling technologies have not been transferred to developing countries, such as China, India, and Nigeria, that generate and import large amounts of e-waste for artisanal recycling.² Consequently, semi-automatic disassembling technologies were developed with the key step to melt solders with equipment, such as infrared heaters,^{28,29} electric heating tubes,^{30,31} and hot fluids, such as diesel and silicon oil, to melt solders.^{29,32–35} These heating methods have very low efficiencies in melting solders, and they frequently result in damaged components because of the differences in heat absorption rates and temperature gradients. Hot liquids used for e-waste recycling also have the added disadvantage of generating large quantities of hazardous waste that need to be further disposed, and bare boards and components need to be further cleaned.

Figure 2. Experimental system: air compressor, UD18A-7, Shanghai United Compressor Co., Ltd., <http://www.sunc.cn/eng/main/index.asp>; compressed air storage tank, 1-0.8, Shanghai Shenjiang Pressure Vessel Co., Ltd., <http://www.sjchuqiguan.com>; frozen compressed air dryer, DSA-36, Shanghai United Compressor Co., Ltd., <http://www.sunc.cn/eng/main/index.asp>; air heater, JRQ-25, Xingtang Electric Heating Equipment Co., Ltd., <http://www.jsyxt.com/>; air tank, 150 (ϕ) $\times$ 500 (h) mm, self-design; temperature sensors, MYWK-01, Mianyang Mingyu Technology Co., Ltd., <http://www.myutech.cn/>; high-temperature electromagnetic valve, HSB-10, Chongqing NaiShi Valve Co., Ltd., <http://www.cq-ns.com/>; and EC automatically disassembling machine, 450 (ϕ) $\times$ 550 (h) mm, self-design.

Table 1. Information of WPCBs

	item ID/model	length (cm)	width (cm)	small surface mount components (side length < 3 mm)	other surface mount components	pin through hole components
1	ASUS MZNSB•AU•SE2	24.5	20.5	440	36	68
2	Abit A-N68SV	24.5	20.5	701	39	68
3		25.5	19	454	21	68
4	FPE H1610SDF•R	24	17	571	26	71
5	PREscott S33	24.5	17	381	16	57
6	YESTON AN68S	24.5	19	838	26	80
7	GAMEN	24.5	20	665	22	78
8	ONDA	25.5	19.5	497	18	67
9	QDI Platinix 2ed v3.0	30.5	20	765	26	99
10	ASUS MZN68•AM•SE	24.5	16.5	471	19	63
11	FPE H1610SDF	24.5	21	808	26	79
12		24.5	20.5	428	36	72
13	GeForce 6100 AM2	24.5	21	541	29	84

Figure 3. TG–DSC results of solders obtained from WPCBAs.

Figure 4. Temperature gradient (a), (b) and velocity field (c), (d) inside the automatically disassembling machine by FLUENT.

In China, e-waste recycling factories are usually located in industrial parks, such as Qingdao New World Eco-industrial Park, where solid waste incinerators are also present. Industrial exhaust heat from these incinerators is typically wasted, with usage less than 30% of generated heat energy.³⁶ Usually, industrial exhaust heat is directly discharged to the environment, causing heat pollution and wasting a valuable source of energy. On

the basis of these premises, this study aimed to design equipment and a procedure for disassembling ECs from WPCBs using industrial exhaust heat, simulated by heated air to melt solders and as pulse jets to separate ECs in a custom-made EC disassembly equipment. The velocity and temperature fields of hot-air flow inside the equipment and parameters that influence disassembling rates were discussed, so that the procedure may be standardized and

Figure 5. Effect of the preheat temperature on the disassembling rate of ECs.

possibly scaled up as a sustainable industrial ecological approach to e-waste resource recovery and energy conservation.

MATERIALS AND METHODS

Sample Collection and Preparation. A total of 13 WPCBAs originating from defunct computers were provided by the New World Environmental Services Group, one of the government-authorized e-waste recycling companies in China. Information for each WPCBA used in this experiment is provided in Table 1, including length and width ranging from 24.0 to 30.5 cm and from 16.5 to 20.5 cm, respectively. All WPCBAs contained between 500 and 1000 different components, mounted on boards by surface mount technology (SMT) and pin through hole technology [PHT, also known as through hole technology (THT)]. As shown in Figure 1, on the basis of these two assembly technologies, all of the mounted ECs were classified to three categories: small surface mount components (SSMCs, side length < 3 mm, generally capacitors and resistors), other surface mount components (OSMCs, generally integrated components), and pin through hole components (PTHCs).

Automatic Disassembling System. Heated air was used in a laboratory-scale automatic disassembling system (ADS; Figure 2) that uses an air compressor to produce compressed air, an air storage tank to store compressed air, an air dryer to remove water, an air heater to heat the compressed air, and an air tank and a high-temperature electromagnetic valve for providing pulse jet to disassemble the mounted ECs (detailed information about all of the equipment used in this system is presented in Figure 2). The ADS is characterized by a cylinder, 450 (ϕ) $\times$ 550 (h) mm, with three support stands. Three pulse jet sources are evenly located on the left, middle, and right of the lower section. The interior diameter of the air inlet/outlet pipe is 15 mm. One is placed 52.5 mm above the lower end, while the other is 114 mm below the top. A stainless-steel grid, inside the machine, is 78.5 mm higher than the bottom pipe, used to load WPCBAs. A temperature sensor near the grid records the temperature at the target WPCBA, and two other temperature sensors, one at the top and the other in the middle, record the temperature field within the ADS. The ADS operates fully covered with heat-insulating materials.

E-Waste Disassembling Procedure. The software FLUENT (version 6.3.26) was used to simulate the temperature distribution and velocity field inside the ADS, with the aim to determine the optimum position of the air inlet. The simulation

(a)

(b)

Figure 6. Photos of (a) exploded electrolytic capacitor and (b) ruined EC.

Figure 7. Effect of the heating source temperature on the disassembling rate of ECs.

conditions were an inlet heating source temperature of 260 °C and an inlet pressure of 0.5 MPa. The outlet was set as natural flow. It was assumed that all of the equipment and machine body were heat-proof, according to the SIMPLE model.³⁷

For each experiment, the ADS was first sealed and preheated to 200 °C and then ventilated to cool to the experimental preheat temperature variable. The WPCBA was inserted into the ADS followed by ventilation to adjust the air heater to the experimental heating source temperature. Three factors were examined: namely, preheat temperature, heating source temperature, and incubation time [beginning when the temperature sensor near the WPCBA reached 190 °C because thermogravimetric differential scanning calorimetry (TG-DSC) results showed that the melting point of the solder, collected from the 13 WPCBAs, is 183.30 °C; Figure 3]. To establish the

Figure 8. Effect of the incubation time on the disassembling rate of ECs.

effect of the preheat temperature ranging from 80 to 160 °C in increments of 20 °C, the heating source temperature and incubation time were set at 260 °C and 4 min, respectively. To determine the effect of the heating source temperature, ranging from 220 to 300 °C in increments of 20 °C, the preheat temperature and incubation time were kept at 120 °C and 4 min, respectively. To determine the effect of incubation times of 1, 2, 4, 6, and 8 min, preheat temperature and heating source temperature were set at 120 and 260 °C, respectively. At the end

of the experimental period, the ADS was cooled to <70 °C to retrieve the ECs. The quantities of the three types of ECs released from the WPCBA were counted. The disassembling rate for component i (x_i) was calculated as the ratio of the number of components released after the experimental procedure (n_i) to the total number of components in the original WPCBA (n_0).

RESULTS AND DISCUSSION

Temperature Distribution and Velocity Field Inside the Automatic Disassembling System. The results of FLUENT software simulation are presented in Figure 4. On the basis of the data, the design of the ADS equipment was modified to better regulate the inflow and outflow of heated air as presented in the simulation. Figure 4 shows the occurrence of vortices identified inside the ADS equipment, and the velocity and temperature field decreased along the air flow circuits and vortices. This observation guided the placement of each WPCBA inside the ADS equipment where the temperature field was even and highest.

Effect of the Preheat Temperature on Component Disassembly. Figure 5 shows the effect of the preheat temperature on the rate of EC disassembly, when the heating source temperature was kept at 260 °C and the incubation period was limited to 4 min. At 80 and 100 °C, the component disassembly rate was zero because no EC dislodged from the WPCBA. However, at 120 °C, the component disassemble rates for SSMCs, OSMCs, and PTHCs increased to 49.12, 100, and 91.18%, respectively. Successively increasing the preheat

Figure 9. Photos of the WPCB (24 × 17 cm) and ECs: (a) WPCB before the experiment, (b) front of the WPCB after the experiment, (c) back of the WPCB after the experiment, and (d) dismantled ECs (preheat temperature, 120 °C; heating source temperature, 260 °C; and incubation time, 2 min).

Figure 10. Industrial designed system for automatically disassembling WPCBAs by industrial exhaust heat.

temperature to 160 °C led to a decline in the disassembly rates for SSMCs and OSMCs to 23.36 and 87.5%, respectively.

At 120 °C, OSMCs, PTH slots, such as peripheral component interconnect (PCI) slots, integrated drive electronics (IDE) slots, memory slots, and power connectors, plug-ins for parallel/serial interface, universal serial bus (USB), PS/2 (used to connect a mouse or keyboard), and speakers/microphones were all successfully disassembled, except the CPU socket. Electrolytic capacitors and batteries, which contain polychlorinated biphenyl and which may ignite, leak potentially hazardous organic vapors or even explode when subjected to heat,² were all disassembled from the board at this condition. At 140 °C, electrolytic capacitors exploded (Figure 6a). At 160 °C, electrolytic capacitors exploded and some plug-ins burnt (Figure 6b).

Effect of the Heating Source Temperature on Component Disassembly. Figure 7 represents the component disassembly rates of OSMCs and PTHCs showing responses to the heating source temperature. For example, when the preheat temperature was increased from 220 to 280 °C, the component disassembly rate of OSMCs and PTHCs also increased from 57.69 and 76.25% to 100 and 97.01%, respectively. Then, the disassembly rates decreased to 88.46 and 78.79%, when the preheating temperature was increased up to 300 °C.

As observed for the effects of the preheat temperature, the disassembly rate for SSMCs was lower than those for OSMCs and

PTHCs. At 260 °C, some electrolytic capacitors exploded, and when the heating source temperature was ≥ 280 °C, some PTHCs were damaged. For the heating source temperatures examined in this study, CPU socket, plug-ins for parallel/serial interface, PS/2, and USB were successfully disassembled from the boards, although plug-ins for parallel/serial interface and PS/2 were damaged when the heating source temperatures exceeded 280 °C.

Effect of the Incubation Period on Component Disassembly. Figure 8 represents data on the effect of the incubation time when the preheat temperature and heating source temperature were kept constant at 120 and 260 °C, respectively. The disassembly rate of SSMCs, OSMCs, and PTHCs did not change when the incubation time was less than 4 min. The subsequent decrease in the rate of component disassembly could be due to the softening of the WPCBA baseboard when subjected to heat for longer than 4 min, leading to the fusion of components. In addition, the disassembly rate of SSMCs was lower than that of OSMCs and PTHCs, the same as the effects of the preheat temperature and heating source temperature. Electrolytic capacitors exploded after 4 min of incubation, and the plug-ins were damaged after 6 min.

Figure 9 shows the images of the WPCBA, the base board, and ECs after disassembly when the preheat temperature, heating source temperature, and incubation period were 120 °C, 260 °C, and 2 min, respectively (the optimum conditions

obtained previously). As shown in panels b and c of Figure 9, almost all of the mounted ECs are successfully disassembled from the WPCB. The disassembling rate of SSMCs, OSMCs, and PTHCs was 39.73, 100, and 98.39%. Figure 9d shows that no EC was damaged.

Industrial Designed System for Automatically Disassembling WPCBAs by Industrial Exhaust Heat. The results of this study demonstrates the feasibility of using heated air to disassemble ECs from WPCBAs through solder melting and pulsating air jet to separate ECs from the base boards. A new equipment and protocol based on this concept is given in Figure 10. In this system, industrial exhaust heat is used as the heating source and steam is used to replace hot air. The scheme (Figure 10a) consists of six parts, industrial exhaust heat, water supply, exhaust-heat boiler, heat exchanger, steam controller, automatic disassembling machine, and waste disposal system. Industrial exhaust heat is used to heat the boiler to produce steam and to heat the low-temperature steam released from the ADS. The steam enters the ADS as a heat source to melt solders and as a pulse jet to dislodge ECs. The low-temperature steam goes to the heat exchanger to raise its temperature. Finally, the steam is condensed to water at ambient temperature and then treated by the waste disposal system.

Figure 10b presents information about the ADS, which is made by four main parts: the inlet, the outlet, the gradual heating chamber, and the pulse vibration disassembling chamber. When WPCBAs are placed in the ADS equipment through the inlet flap valve, they drop to the preheat conveyor and are heated by the steam from the pulse vibration disassembling chamber. The WPCBAs are then conveyed to the high-temperature grid conveyor and heated by the steam, after which ECs are dislodged by vibration and pulse jet. In this system, WPCBAs are heated evenly because steam is used to replace hot air, the heat capacity of which, $4.18 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$, is much higher than that of air, benefiting the heating process. The temperature in the pulse vibration disassembling chamber can also be monitored and controlled to avoid the potential release of toxic chemicals.^{2,9}

This research presents an innovative strategy for recovering, for the first time to our knowledge, ECs from WPCBs without damage and reusing industrial exhaust heat at the same time. Thus, a novel, energy saving, and environmental friendly technology for dismantling ECs from WPCBs and for effective use of industrial exhaust heat is described to advance the evolving e-waste recycling industry while also conserving energy. Further work is ongoing to scale up the process to industrial production levels.

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Notes

The authors declare no competing financial interest.

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