Hands-on Training of Engineering Students on Recycling of Electronic Waste Materials

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Abstract

E-waste is a common name of electronic products at the end of their useful life. A number of e-wastes coming from old and used computers, televisions, cellphones, radios, VCRs, stereos, copiers, and fax machines are highly popular electronic products. Because of the highly valued precious metals in those electronic devices, some of these products can be recycled, reused and refurbished for the same and other applications. Consumer Electronics Association estimated that an average person owns 24 electronic products. According to the forecasts by 2017, the world will generate around 33 percent more e-waste, (or 65 million metric tons). One of the primary driving force behind recycling of e-wastes include environmental concerns, economic, public health and data security (in the storage systems). In this study, the undergraduate engineering students were trained on recycling of e-waste for the recovery of precious metals, such as gold. The recycling process was conducted in different steps: step 1 for stripping the gold fingers (bars); step 2 for treating the gold films/foils; step 3 for dissolving gold; and step 4 for melting. Various types of electronic wastes ware collected, and then stripping process was applied on gold fingers/bars which was originally obtained from circuit boards. During the dissolution process, copper chloride, hydrochloric/nitric acid and distilled water were mixed together, and gold fingers were immersed in this solution for about a week. Sodium metabisulfate was added to the solution to get gold precipitates. Later gold precipitates were heat treated to recover the extracted gold. The major goals of this study were to reduce the electronic wastes, find best recycling option for the e-waste processing and train engineering BS students.

Keywords: Recycling, E-waste, Gold Extraction, Melting, Precipitation, Gold Recovery, Student Training.

1. Introduction
1.1 General Background

Industrial revolution and advancements in new technologies have rapidly changed the world's life styles. Electronics have taken away the utmost place in human's daily life, and it has improved to a level where a person can get multiple electronic products for daily use. One of the greatest disadvantages with the electronic gadgets is to properly dispose / recycle the used electronics. Every year 20-50 million metric tons of e-waste are discarded in the world. This figure will substantially grow in the near future [1-4].

Europeans approximately generated 20 kg of e-waste/person/year [1]. Total e-waste produced in the U.S. was 3.412 million tons in 2012. Nevertheless, substantial increase in the growth of the electronic devices has not be considered for collection, recycle and reuse [2]. Chain, U.S.A. and

Europe are the major producers and consumers of the electronic devices. As technology increases, the life times of the electronic devices are reduced, thereby increasing the amount of e-waste gradually. Thus, there is a great need for end of life management options for each electronic device. The Waste Electrical and Electronic Equipment Directive aims at minimizing the impacts of the end of life of electrical and electronic products and goods on the environment, by either reusing or recycling and thus reducing the overall waste disposal.

Scrap is composed mainly of metals and alloys (e.g., Au, Ag, Pt, Pd, Cu, Al, Ni, Ti, Fe, Hg, Cd, Pb, etc.), thermoplastic and thermoset plastics, refractory oxides, rare earth elements (Ce, Er, Gd, La, Nd, Sm, Y, etc.), and n and p types of semiconductors and their components (e.g., doped Si, Ga, As, Ge, In, P, B, Bi, etc.) [3]. Electronic devices can contain up to 60 different elements, many of which are valuable ones, such as precious and special metals (e.g., Au, Ag, Pd, and Pt). Some of the metallic e-wastes and their compounds (soldering) are considered to be hazardous (e.g., Hg, As, Cd, Pb, etc.). Recycling electronics can substantially reduce the environmental impacts of manufacturing products from raw materials and reduce the cost and landfill wastes [1].

Naturally occurring pure metallic elements can have a higher melting point, and more ductile compared other alloy metals for different industrial use [4]. For a number of reasons, such as economic, environmental, public health and data security, these e-wastes are needed to be collected, recycled and reused. Precious metals are very rare and expensive. Electric and electronic industries are the major consumers of the precious and special metals; thus, it is highly recommended that these metals and compounds are precisely recovered and reused for the industry because these precious metals are limited on the earth crust. However, recovering and reusing parts of e-wastes have not been developed as much as the device productions. Table 1 shows the compositions of the electronic devices that have various precious metals [1].

Table 1: Composition of electronic devices with various amount of precious metals [1].

Electronics	**Copper (% by weight)**	**Silver (ppm)**	**Gold (ppm)**	**Palladium (ppm)**
Television (TV)	10	280	20	10
Personal Computer (PC Board)	20	1000	250	110
Mobile Phone	13	3500	340	130
Portable Audio Scrap	21	150	10	4
DVD Player Scrap	5	115	15	4

Most of the circuit boards and their compounds comprise the highest value of precious metals, as well as some of the heavy metals [5]. The components of a PC have the highest economic value, owing to the gold plated connectors, components, pins and transistors, which are also called fingers. The gold plating has a better advantages because of the high corrosion resistance and better electrical and thermal conductivities. Some of the examples are given below for e-waste:

- Motherboard (main circuit board and their connection parts)
- Peripheral Component Interconnect (PCI) boards
- Random Access memory (RAM) (long, rectangular and small circuit boards)

- Processor (large chip that plugs directly into the mother board).

It is estimated that 50-80% of e-wastes collected in industrialized countries are exported to developing countries such as China, India, Pakistan, Vietnam, Turkey and Bangladesh due to the cheap labor and lenient environmental rules and regulations. These developing nations have a lacking health and safety issues, and consequently workers handle the toxic metals without proper equipment and training. New regulations should be developed and supported with the law to enforce recycling firms and protect workers life as well as our fragile nature.

1.2 End of Life Options for E-wastes

End of life analysis is one of the important subjects to determine all the possibilities of e-waste from mining operation to landfilling. The end of life options for E-waste are as follows:

- Reuse of functional electronics
- Refurbishment and repair of electronics
- Reuse and recovery of electronic components
- End processing for recovering metals
- Disposal and landfilling.

Considering all these options, reuse and refurbishment seem to be the best options among the others; however, the process should be working and must be functional for the same or other applications. If it is not functional and reliable to use, then the best option is to recycle those valued elements and reuse them for the same or different industrial applications. This allows manufactures and consumers to collect the precious metals and reduces the effects of environment and public health, as well.

1.3 E-waste Processing

In order to increase the economic, health and environmental benefits of e-wastes, e-waste procession can be generally performed in three different steps, including collection, sorting and end procession. These steps are quickly summarized below:

Collection: Collection of the e-waste commonly means taking all levels (from the national level to the regional) e-wastes at houses, factories, municipal buildings and other relevant stores and shops. There are a number of “take back programs” from sponsors, companies, retailers and manufacturers, drop off collection centers, profit and nonprofit collection centers in various places.

Sorting: Sorting is a process of separating e-wastes at a regional level or national level, and has the end goal for device streams into different categories, such as material streams, primarily metals, glass, composites and plastics. Figure 1 shows the advanced recycling unit located in California. The major goal of this stage is to separate the valuable material for using in the future manufacturing and processing steps. Remaining parts will be removed and safely disposed to the landfill. Note that the optimal level preprocessing is generally dictated by the quality and quantity of feed requirements and end processing needs.

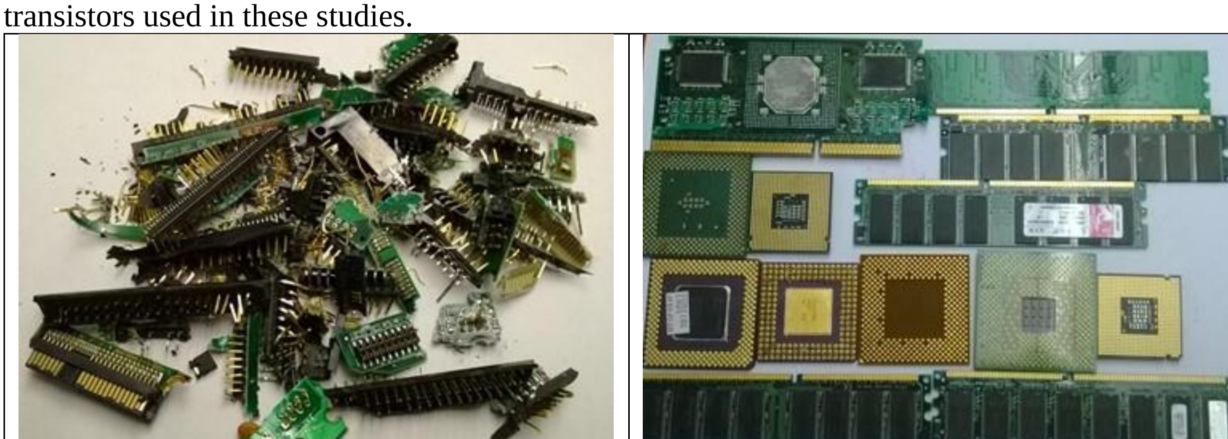
Figure 1: Advanced recycling unit located in California (Sims Recycling Facility in Roseville, California).(http://www.wired.com/gadgets/miscellaneous/news/2009/03/gallery_ewaste_recycling?currentPage=all)**.**

End Processing: The goal of the end processing step is to recover the valuable components (e.g., precious metals, other metals and alloys, composites, ceramics and plastics) and remove impurities and unsafe parts from the stream. Sampling and assaying are the necessary steps in order to determine the compositions of recyclable materials in the e-waste stream and to ensure that the optimum processing is used to recover those e-waste materials and devices.

2. Experimental

2.1 Materials

Gold carrying fingers collected from the circuit boards of the old computers to recover precious metals. Figure 2 shows the circuit boards, and gold plated connectors, components, pins and transistors used in these studies.



a) b)

Figure 2: Images showing a) the collected gold plated connectors, components, pins and transistors in b) the motherboard, peripheral component interconnect board, random access memory, and processor.

2.2 Methods

The first step is to collect the scrap and separate the gold fingers from the e-waste scrap. There are several types of circuit boards available, but are not treated in same kind because of the manufacturing specifications. In this process, various processes, including collection of gold fingers, shearing/cutting, burning with torch, and acid treatment were applied on the e-wastes. Many of the circuit boards also contain the connector edges, which were cut and separated after shearing / cutting by scissors. The amount of the film thickness on those substrates can be usually between 0.5 and 50 μm. In some of the collection process, propane torch was used to remove the gold fingers from the circuit board because they were attached to the board via soldering (low melting materials) process. At a higher temperature, solders were melted to free the gold coated finger. However, this process cannot be used on all types of circuit boards. The gold fingers and connector edges are then treated in acid to receive the gold films/foils. There are three key ingredients which drives the stripping forces of electroplating, including copper chloride, dissolved oxygen by air bubble and HCl solution. Figure 3 shows the air bubbling/oxygenation and gold films / foils removing process in a plastic cup with HCl and copper chloride solution.

Figure 3: The air bubbling / oxygenation and gold films removal process in an acidic solution.

These gold foils are generally applied on copper and nickel sheets on the boards. Figure 4 shows the gold film recovery process on nickel and copper layers of the printed circuit boards (PCBs). In this process, copper and nickel layers are preferentially dissolved / etched to receive gold films in the oxygen reach solution. Dissolved oxygen is basically the oxidizing reagent to produce a soluble copper and nickel salts in the solution. Depending on temperature, amount of free acid, aeration rate and time, and level of agitation / mixing [6], the stripping process last anywhere from 24 hours to a week. During the process, when the solution level was dropped, additional DI water was added to keep the solution level constant. This process involved highly corrosive acids and solutions, and was conducted under the fume hood. Thus, the engineering students used various safety equipment, such as goggles, respirator devices, lab cloth, and gloves which are mandatory during the gold recovery process.

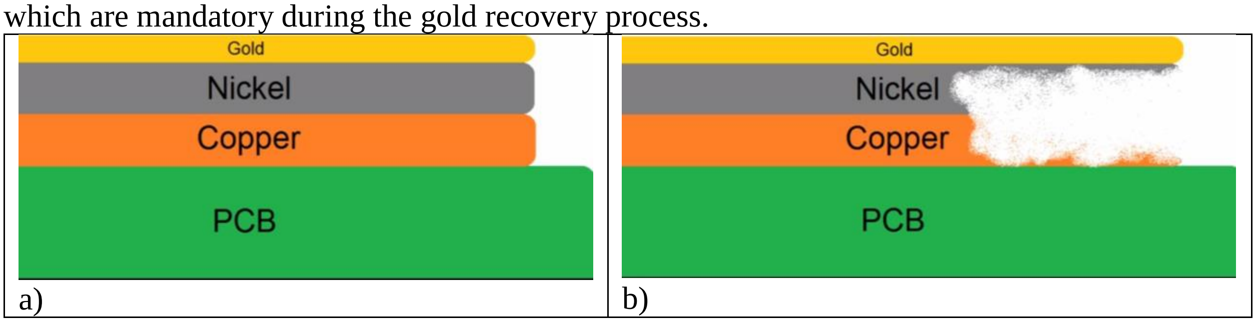


Figure 4: a) Initial gold film recovery process, and b) dissolved nickel and copper layers on the printed circuit boards.

3. Results and Discussion

After the stripping process was completed, the gold coated fingers were removed, washed with DI water and then the gold foils were collected from the solution cup. In order to remove the gold from the reaction cup, the larger pieces were taken away manually, and the solutions with the gold foils were filtered using a standard filter paper. The gold foils were washed with DI water a few times to remove any excess of copper chloride and HCl solutions [6]. After the drying process, the collected gold films were fired into a high temperature ceramic crucible using furnace and propane torch. Figure 5 shows the gold coated fingers and boards after the etching solution, gold foil reach solution and filtered gold foils.

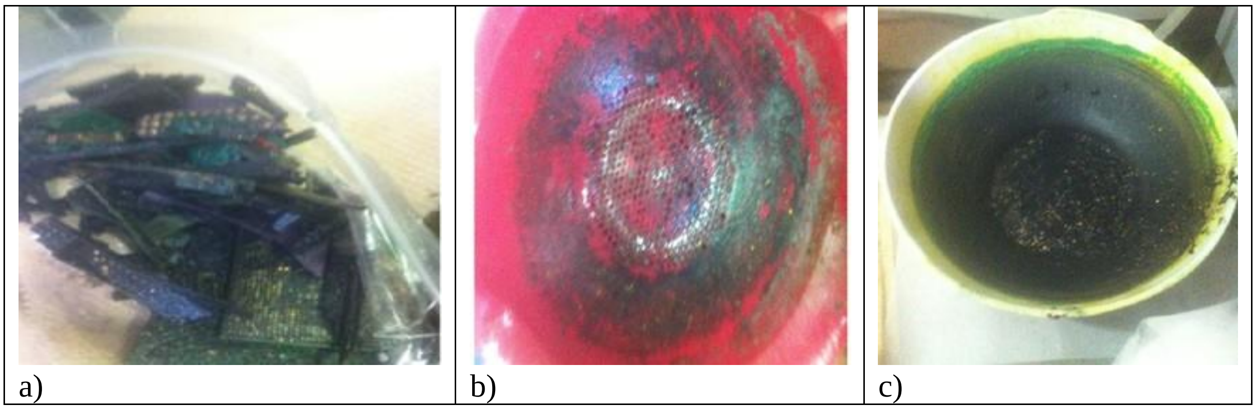


Figure 5: Images showing a) the gold coated fingers and boards after the etching solution, b) gold foil reach solution, and c) filtered gold foils (small yellow color pieces) for further processing.

The collected gold foils were placed in a beaker in which a diluted HCl solution was added, and loosely covered by a parafilm before heating the medium about 50-70 °C. After the solution was reached the specified temperature, a small amount of concentrated nitric acid (~5-10 vol.%) solution was added in the same beaker (usually 3-6 ml of nitric acid per beaker) [6]. As the gold, copper and other trace elements (e.g., Fe, Ni, Co, Sn, and Pb) were dissolved into the solution, the solution color was then turned into yellow/orange color. Later, the gold reach solution was filtered again to separate gold reach solution from the impurities.

To selectively precipitate the gold from the solution, sodium metabisulfite (SMB - $Na_2S_2O_5$) was used. The SMB was first dissolved in DI water and then added to the gold reach solution to react with the gold ion in the solution and reduce it to metallic gold precipitant form. Based on the simple redox reaction, the SMB may reduce the gold ions to its elemental state of Au powder:

$$Na_2S_2O_5 + H_2O \longleftrightarrow NaHSO_3$$
$$3NaHSO_3 + 2HAuCl_4 + 3H_2O \longleftrightarrow 3NaHSO_4 + 8HCl + 2Au$$

The precipitation flask was allowed for 24 hours to ensure all of the gold particles were settled down to the bottom of the beaker. Using the DI water, the precipitated gold particles were washed a few times. All the DI water was removed and the gold powder was allowed to dry at room temperature before the melting process.

The precipitated and washed Au precipitants were placed into a high temperature ceramic crucible, and placed into a small furnace before heating up to 1100 °C. After about 30 minutes later, the precipitated gold was turned into a small piece. Note that melting temperature of pure gold is 1064 °C. A propane torch was also used to accelerate the gold powder into a metallic form. However, amount of gold recovered from the furnace was slightly higher than the torch flame process. High speed flame may remove some of the small gold particles during the torching process. More characterization studies on the produced materials will be conducted in the future studies. As a result, the precious metals can be the major sources of raw materials for the electronic industries and reduce the environmental and health concerns worldwide.

4. Hands-on Experiences for Engineering BS Students

Due to the environmental and health concerns of e-waste and devices, new generations of recovery processes are needed to recover all the precious metals into the electric and electronic devices, and parts. Recycled metals, such as Au, Ag, Pt, Pd and other highly valued metals, plastics and semiconductors can be used as the major raw sources of manufacturing processes for the same and different industries. Department of Mechanical Engineering at WSU has more than 600 undergraduate students and a big portion of these students are highly considering on doing hands-on experiences during their studies. One of the BS students (Mr. Subeshan Balakrishnan) was involved in the present study, learned many new techniques and gained a lot of new skills and knowledge about recycling, e-waste, recovery processes, and other related technologies[7-10]. The student has used these research activities as his own Engineer of 2020 requirements in the College of Engineering. This student is also co-author of the present study and made a lot of contributions during the experiments. It is believed that these hands-on trainings and new technologies will enhance the knowledge of many engineering BS students to perform more detailed studies in the field.

5. Conclusions

Recycling and recovering of e-wastes are fairly limited processes due to the insufficient collection, lack of federal legislation or policy mandating on e-waste recycling, un-matured recycling and recovering technologies and illegal exports of hazardous e-waste to developing countries where recycling process pose serious risks to human health and environment. Recycling is a great option to recover the precious metals from e-wastes and use in the same or different industries as raw secondary materials. In order to address some of the e-waste concerns, our research team collected the gold plated connectors, components, pins and transistors in the motherboard, peripheral component interconnect board, random access memory, and processor. After the collection process, dissolution, precipitation and melting processes were applied to recover the gold from the e-waste. This will certainly allow a sustainable growth in electronic industries. One BS student was involved in this project and used these research activities for his Engineer of 2020 requirements. We believe that these studies can greatly benefit undergraduate engineering students for their future academic studies in the field.

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Biographical Information

Gopi Krishna Mandadi

Mr. Gopi Krishna graduated with a MS degree from the Department of Mechanical Engineering at WSU. During his studies, he has been working on the recycling related projects and process developments.

Subeshan Balakrishnan

Mr. Balakrishnan is a BS student in the Department of Mechanical Engineering at WSU. After the graduation, he will be joining the graduate school at WSU and will focus on the nanotechnology and renewable energy systems.

Dr. Eylem Asmatulu

Dr. Asmatulu is currently an Engineering Educator in the Department of Mechanical Engineering at WSU and actively involving in teaching, research, and scholarship activities in the same department. She received her PhD degree from the Department of Industrial and Manufacturing Engineering at WSU in May 2013, which was mainly focused on the “Life Cycle Analysis of the Advanced Materials”. Prior to the WSU, she also worked in the Environmental Health and Safety at WSU and Composite Manufacturing Laboratory at NIAR of WSU. Throughout her studies, she has published 8 journal papers and 23 conference proceedings, authored 8 book chapters, presented 8 presentations, and reviewed several manuscripts in international journals and conference proceedings. Dr. Asmatulu is currently conducting research on “e-waste recycling, water recycling, active carbon processing, algae based biofuel productions and CO_2 capturing”.