Automatic Sorting of Small Electronic Device Scraps to Facilitate Tantalum Recycling

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Abstract
After precise dismantling of 49 scrap cellular phone models released between 1999 and 2007, it was found that the average number of tantalum condensers used in the cellular phone models decreased significantly after 2005. The automatic sorting technique which combines a weight meter with a laser three-dimensional shape-detection system was used to identify whether a scrap cellular phone was released before 2004 or after 2005. As the result, the automatic sorting technique was adequate for separating 191 different scrap cellular phone models into those two groups. In addition, automatic sorting of various other small electronic devices into three groups based on resource value was achieved with high accuracy.

Key words: Tantalum, Recycling, Sorting, 3D shape, Weight

1. Introduction

In order to recover rare metals from small scrap electronic devices, it is necessary to separate out the electronic components containing those metals before they undergo conventional nonferrous metal smelting. In this study, we focus on tantalum condensers, which contain tantalum at approximately 30 wt%. If such condensers could be removed from printed circuit boards and collected by a special physical separation process that takes into account differences in size, shape and density, it becomes possible to realize a new, commercially viable, domestic tantalum recycling loop. Since the number of tantalum condensers in small electronic devices depend on the product type and/or year of release, it is reasonable to assume that if scrapped devices are sorted according to these factors it would lead to effective recycling of tantalum. Namely, as shown in Fig. 1, if tantalum rich devices (Group A) and tantalum poor devices (Group B) are separately fed into different physical separation processes, small-scale dismantling and large-scale crushing or roasting, it would facilitate precise dismantling of the Group A devices and collection of tantalum-rich printed circuit boards with relatively low cost.

Although manual sorting is the primary method to classify scrapped devices according to their product types and/or release years, its labor cost is problematic in advanced countries and its processing rate is much lower than automatic sorting. As for automatic sorting technologies, such as those employing near-infrared spectroscopy, color, X-ray fluorescence, can only detect the surface properties of the object under inspection. They cannot be used to detect rare metals in devices because the targeted printed circuit boards are covered with various-colored plastic and/or metallic cases. Although X-ray transmission sorter which gauge differences in atomic density or optical sorter which utilize two-dimensional imagery analysis can potentially be used, there are doubts relating to their applicability to a variety of different product types. Although prompt-gamma neutron activation analysis technique which can identify the elements existing within an object without contact may be available in the future, this technique has not yet been completed as a sorter.

The purpose of this study is to ascertain the applicability of our developed automatic sorting technique, which combines a laser 3D shape detection system and a weight meter, to the separa-
tion of small scrap electronic devices. We begin by discussing the relationship between the numbers of tantalum condensers used in cellular phone models and their year of release. Then, the trends on the weight and 3D shape design of cellular phones over time are discussed based on data obtained via the developed sorting system. In the next step, we demonstrate the automatic sorting of scrap cellular phones into two groups according to their year of release, while also discussing the number of tantalum condensers in other small scrapped electronic devices, such as digital cameras, CD players, etc., and demonstrate that such devices can be automatically sorted into three groups according to the product type.

2. Demands for tantalum recycling

After the sudden rise in the import prices of rare metals and rare earth metals in 2010, the Japanese government announced a priority program under which the following products and elements would be aggressively collected and recycled:

- Tantalum condensers: Ta
- Neodymium magnets: Nd, Dy
- Lithium-ion batteries: Co
- Cemented carbide tools: W

These elements and products were carefully selected from the viewpoints of their supply-demand imbalance and the technical feasibility of recycling them. Since that time, recycling technologies aimed at their recovery have been aggressively pursued.

The market prices of these metals, as of May 1, 2012 and of April 1, 2014, are listed in Table 1. As can be seen in the table, tantalum is almost ten times the price of cobalt and tungsten, and is far more expensive than copper and nickel. Since electronic device makers took action to replace tantalum with ceramic condensers after the price surge around 2000, tantalum condensers have been increasingly replaced by ceramic condensers in most small electronic devices, yet remain essential for automobile electronics, personal computers (PCs), aircraft components, and in space industry applications. Therefore, securing a secure source of tantalum remains important for ensuring the stable production of tantalum condensers in the future.

3. Experimental

3.1 Scrap cellular phones

A total of 191 different cellular phones, from which the batteries had been removed, were recovered from scrapped devices collected at a recycling plant in Japan. First, all the selected cellular phones were sorted by hand according to the release year of each model. Next, the number of tantalum condensers installed on the printed circuit boards of 49 different models that had been released between 1999 and 2007 were manually checked after precise dismantling. In the automatic sorting experiment, 90 different scrap cellular phone models released before 2004 (Group A) and 101 different models released after 2005 (Group B) were used. Some of the samples in both groups are shown in Fig. 2.

3.2 Small scrap electronic devices

A total of 66 different small electronic devices (covering 29 device types) released between 1995 and 2005 from Japanese manufacturers were used as samples. These devices are listed in Table 2.

![Fig. 1 Objective of the automatic sorting of small scrap electronic devices.](image-url)
These devices were classified into three groups from the viewpoint of their inherent resource value, i.e., the tantalum and the other valuable metals (such as copper, silver, and gold) inside. Group A devices contain both tantalum and valuable metals at high concentrations. Group B models are those that contain relatively high levels of other valuable metals, but low tantalum. Group C models are low in both tantalum and valuable metals.

First, the numbers of tantalum condensers on the printed circuit boards of 29 different devices (digital cameras, MD players, CD players, electronic dictionaries, and digital game players) were manually checked, after which the devices were automatically sorted into the three groups.

3.3 Automatic sorting system

The automatic sorting equipment used is the same as that used in our previous studies. This system consists of two stage vibration feeders, a conveyer belt, a weight meter, a laser 3D shape detection camera, a mini-sorter unit operated by an air-cylinder, and a PC for system control. This sorting system offers the following advantages. First, the initial and running costs for the instruments are relatively low. Second, the sorting accuracy is not affected by scrap surface contamination. Third, identification algorithm neural network re-learning makes it possible to continuously improve sorting accuracy.

As mentioned in our previous studies, a primary database was prepared based on eight measurements of each scrap device, which were obtained by changing the device posture on the conveyor belt. The registered data are a combination of variables (listed in Table 3) obtained via a one-time measurement (referred to hereafter as one case). A newly developed algorithm obtained from a data matching technique using neural network was used to identify the correct group for each inspected device. First, all of the case data were sorted and categorized into several sections according to apparent density or other variables. A schematic diagram of the algorithm to identify whether a cellular phone belongs to Group A or B are shown in Fig. 3. The ones of apparent density \( X_1 \geq 3.0 \text{ g/cm}^3 \) and \( X_1 < 0.75 \text{ g/cm}^3 \) were immediately identified as Group B and A respectively. Neural network analysis were applied to the other apparent density sections. For example, the ones of \( 0.93 \leq X_1 < 1.01 \text{ g/cm}^3 \) were identified with two neural networks defined for the case data in two sub-sections based on the order of vertically projected area \( X_3 \). The value \( m \) was set to equalize the number of case data in each sub-sections. These threshold values of \( X_1 \) and \( X_3 \) were saved in a parameter setting file. In order to construct neural network structure and optimize weight and thresh-

| Group A | Group B | Group C |
|---------|---------|---------|
| Digital cameras 16 (models) | CD players 4 (models) | Remote controls 3 (models) |
| MD players 5 | Cassette tape players 5 | PC mice 6 |
| HDD player 1 | Electronic dictionaries 6 | AC adapters- light 3 |
| Portable game player-new 1 | Portable game player-old 1 | Battery chargers 2 |
| AC adapters- heavy 3 | Network hubs 2 | Switch boxes-large 2 |
| Calculator 1 | Scanner-small 1 | Switch boxes-small 2 |
| Printer-small 1 | ZIP drive 1 | |

| Table 2 Small scrap electronic devices used in this study |

| \( X_0 \): Material (group) | \( X_1 \): Width | \( X_0/0 \): \( X_0/(X_1 \cdot X_5) \) |
| \( X_2 \): Weight/Volume (apparent density) | \( X_1 \): Maximum height | \( X_1/0 \): \( X_1/X_6 \) |
| \( X_3 \): Volume | \( X_2 \): Height of the center of gravity | \( X_3/0 \): \( X_3/X_7 \) |
| \( X_4 \): Vertically projected area | \( X_4 \): \( X_4/X_5 \) | \( X_4/1 \): \( X_4/X_7 \) |
| \( X_5 \): Length | \( X_0/5 \): \( X_0/(X_5 \cdot X_5) \) | \( X_0/4 \): \( X_0/X_4 \) |
old values of each neuron, we used conventional neural network analysis software which can generate a network setting file containing these values. Similar calculation procedure were performed in the other apparent density sections, and all of the network setting files and parameter setting file were obtained. In the case of small scrap electronic devices sorting, the parameters of $X_3$ and $X_6$ were used instead of $X_1$ and $X_3$, respectively.

Our own data processing software developed for the automatic sorting system can be operated by two different modes. The normal mode was used to identify “unknown” samples. We can control the actions of the sorting system, load the network setting files and the parameter setting files, indicate and save the measured data and the result of identification. On the other hand, the learning mode was used to modify the database and identification algorithm by feeding “known” samples. To re-write the weight and threshold values of neural networks, we can set target values of correctly identified rate and maximum calculation step etc., and can monitor the transition of the error value obtained by the back propagation method.

The sorting experiment was carried out under the conditions of 1.5 m/s belt speed and one piece/s processing speed. Each sample was inspected four times at different posture on the conveyor belt, and the group of each scrap was inspected individually by a calculation substituting the measured values of $X_1$–$X_{14}$ into the data processing software.

4. Results and Discussion

4.1 Cellular phone sorting

The numbers of tantalum condensers found in the 49 different scrap cellular phone models released between 1999 and 2007 are listed in Table 4. Here, we can see that number of tantalum condensers per phone varies widely between two and 26, and that the average number gradually decreases over time. In particular, the average number decreases most significantly between 2004 and 2005. This suggests that efforts to substitute ceramic for tantalum condensers advanced significantly around 2005. Furthermore, although the relative sizes are not shown here, we also confirmed the downsizing trend for tantalum condensers, as well as other electronic components. Based on the above, from the viewpoint of effectively recovering tantalum from scrap cellular phones, we could reasonably conclude that sorting scrap devices according to their year of release is an effective method, and that only those ones released prior to 2004 should be fed into the new precise dismantling recycling process, while the others could be directly fed into conventional mechanical processes aiming at recovering valuable metals.

The cumulative distributions of a number of variables measured by the developed sorting system for Groups A and B are compared in Fig. 4. The differences in these data suggest that cell phone designs have changed over the time. As a general trend, they have become larger and thinner and have increased in apparent density. As a result, we can use our sorting technique to determine whether a scrapped cellular phone belongs to Group A or B.
The results of the sorting experiment using 191 scrap cellular phone models are summarized in Table 5, which shows the rate of correctly sorted devices for four groups, including samples that were not registered in the primary database (indicated by “-ur”). As shown in this table, using the primary database and the abovementioned algorithm, the rate for correctly sorted unregistered samples did not deteriorate significantly in comparison to registered models, and a total overall success rate of 86.8% was obtained. After the primary database was modified by adding failure case data, the algorithm was improved via neural network re-learning. This improved the rate of correctly sorted devices to 88.2% in total. Repeating this procedure three times allowed us to achieve a rate of correctly sorted devices that exceeded 90%, both in each group and in total. Since this experiment was carried out under the conditions of 1.5 m/s belt speed and one piece/s processing speed, we can safely say that the developed automatic sorting system is far more effective than manual sorting.

4.2 Small electronic device sorting
The numbers of tantalum condensers found in the 29 different digital camera, MD player, CD player, electronic dictionary, cassette tape player and digital game player models are listed in Table 6. We considered it likely that almost all of these products had been released before 2005, even though the release year of some devices could not be verified. As seen in this table, the number of tantalum condensers in a small electronic device strongly depends on the product type. More specifically, digital cameras and MD players of this era contain significant numbers of tantalum condensers, and thus are promising as a secondary tantalum resource. It is generally known that, reflecting their high performance levels, these products contain other valuable metals.
at concentrations similar to cellular phones. Although devices released after 2005 were not sampled in this study, since these products and cellular phones were produced via the same industry in Japan, it seems reasonable to assume that the trend of substituting tantalum condensers with ceramic models would be similar. This, in turn, suggests that automatic sorting by the release year is important for Group A devices after they have been identified. On the other hand, CD players, cassette tape players, electronic dictionaries, and portable digital game players do not contain tantalum condensers in significant amounts, even if they were released prior to 2005, although they do contain valuable metals at relatively high concentration levels.

As described in Table 2, we classified 66 different models (20 device types) of small electronic devices into three groups (A, B, and C) from the viewpoint of resource value, performed automatic sorting of these scrap devices into the three groups, and then examined the results. Those results are summarized in Table 7, which also shows the correctly sorted rate for four groups (one group for unregistered samples) into the primary database. Here, two-stage sorting was employed. In the first stage, Group A devices are separated out, after which Group B and C separation is performed in the second stage. As seen in this table, small electronic device sorting is much easier when compared to cellular phones because the differences in 3D shape among electronic devices are particularly significant. After the primary database and the identification algorithm were mod-

### Table 6 Number of Ta condensers found in six scrap electronic device types (29 models)

| Year | Maker | Ta condensers |
|------|-------|---------------|
| 1995 | F     | 46            |
| 1996 | CS    | 23            |
| 1999 | O     | 8             |
| 2000 | O     | 10            |
| 2000 | F     | 46            |
| 2000 | O     | 19            |
| 2002 | CA    | 18            |
| 2002 | SO    | 32            |
| 2003 | F     | 15            |
| 2004 | CA    | 22            |
| 2004 | CS    | 11            |
| **Average** | **22.1 pieces** |

### Table 7 Results of the small scrap electronic device automatic sorting experiment

[1st sorting between A and B, C]

| Data base  | Group A (16 models) | Group A-ur (7 models) | Group B, C (12 models) | Group B, C-ur (31 models) | Total (66 models) |
|------------|---------------------|-----------------------|------------------------|---------------------------|-------------------|
| Primary    | 100                 | 90.0                  | 97.9                   | 72.4                      | 85.9 (227/264)    |
| Modified 1 | 92.2                | 53.1                  | 100                    | 96.0                      | 90.7 (240/264)    |
| Modified 2 | 100                 | 100                   | 100                    | 96.0                      | 98.1 (259/264)    |

[2nd sorting between B and C]

| Data base  | Group B (19 models) | Group B-ur (6 models) | Group C (8 models) | Group C-ur (10 models) | Total (43 models) |
|------------|---------------------|-----------------------|-------------------|------------------------|-------------------|
| Primary    | 98.7                | 95.8                  | 100               | 100                    | 98.8 (170/172)    |
| Modified 1 | 98.7                | 100                   | 100               | 100                    | 99.4 (171/172)    |
ified two times or less, the rate of correctly sorted devices exceeded 98%. Although further study will be necessary under conditions involving larger numbers of models and devices before this sorting system can be put into practical use, it seems quite probable that the system can be applied to large-scale processing because the neural network re-learning process in the identification algorithm is helpful for maintaining sorting accuracy.

5. Conclusions

From the viewpoint of recovering tantalum and other valuable metals, automatic sorting of small scrap electronic devices according to the year of release and product type was demonstrated by using an advanced sorting technique that combines a laser 3D shape detection system and a weight meter. The test samples were 191 different cellular phone models released between 1999 and 2007 that had been recovered from scrap, and 66 different other scrap small electronic devices (29 device types) released between 1989 and 2005. The results obtained in the present study are summarized as follows:

1. The number of tantalum condenser used in a cellular phone strongly depends on the year of release and the average number largely decreased after 2005.

2. As a general trend, cellular phones have become larger and thinner in size, and have increased in apparent density over time. Thus, the developed sorting technique is helpful for identifying whether a scrap cellular phone was released before 2004 or after 2005.

3. Automatic sorting of scrap cellular phones into two groups based on the year of release can be achieved with a sorting accuracy of over 92%.

4. Digital cameras and MD players released before 2004 contain significant numbers of tantalum condensers and are promising as a secondary tantalum resource.

5. Automatic sorting of small scrap electronic devices three groups based on product type can be achieved with a sorting accuracy of over 98%.

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