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Journal of Hazardous Materials B99 (2003) 243–263
Journal of Hazardous Materials
www.elsevier.com/locate/jhazmat

Mechanical recycling of waste electric and electronic equipment: a review

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Received 16 August 2002; received in revised form 12 February 2003; accepted 13 February 2003

Abstract

The production of electric and electronic equipment (EEE) is one of the fastest growing areas. This development has resulted in an increase of waste electric and electronic equipment (WEEE). In view of the environmental problems involved in the management of WEEE, many counties and organizations have drafted national legislation to improve the reuse, recycling and other forms of recovery of such wastes so as to reduce disposal. Recycling of WEEE is an important subject not only from the point of waste treatment but also from the recovery of valuable materials.

WEEE is diverse and complex, in terms of materials and components makeup as well as the original equipment's manufacturing processes. Characterization of this waste stream is of paramount importance for developing a cost-effective and environmentally friendly recycling system. In this paper, the physical and particle properties of WEEE are presented. Selective disassembly, targeting on singling out hazardous and/or valuable components, is an indispensable process in the practice of recycling of WEEE. Disassembly process planning and innovation of disassembly facilities are most active research areas. Mechanical/physical processing, based on the characterization of WEEE, provides an alternative means of recovering valuable materials. Mechanical processes, such as screening, shape separation, magnetic separation, Eddy current separation, electrostatic separation, and jigging have been widely utilized in recycling industry. However, recycling of WEEE is only beginning.

For maximum separation of materials, WEEE should be shredded to small, even fine particles, generally below 5 or 10 mm. Therefore, a discussion of mechanical separation processes for fine particles is highlighted in this paper.

Consumer electronic equipment (brown goods), such as television sets, video recorders, are most common. It is very costly to perform manual dismantling of those products, due to the fact that brown goods contain very low-grade precious metals and copper. It is expected that a mechanical recycling process will be developed for the upgrading of low metal content scraps.

Keywords: Recycling; Electronic scrap; Waste treatment; Material recovery

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0304-3894/03/$ – see front matter
doi:10.1016/S0304-3894(03)00061-X

1. Introduction

The production of electric and electronic equipment (EEE) is increasing worldwide. Both technological innovation and market expansion continue to accelerate the replacement of equipment leading to a significant increase of waste electric and electronic equipment (WEEE). In west Europe, 6 million tonnes of WEEE were generated in 1998, the amount of WEEE is expected to increase by at least 3–5% per annum [1]. In the USA, a recent study predicted that over 315 million computers would be at end of their life by the year 2004 [2].

Due to their hazardous material contents, WEEE may cause environmental problems during the waste management phase if it is not properly pre-treated. Many countries have drafted legislation to improve the reuse, recycling and other forms of recovery of such wastes so as to reduce disposal [1,2].

Recycling of WEEE is an important subject not only from the point of waste treatment but also from the recovery aspect of valuable materials. The US Environmental Protection Agency (EPA) has identified seven major benefits when scrap iron and steel are used instead of virgin materials. Using recycled materials in place of virgin materials results in significant energy savings (as shown in Tables 1 and 2) [3].

Currently, recycling of WEEE can be broadly divided into three major stages:

- Disassembly (dismantling): selective disassembly, targeting on singling out hazardous or valuable components, is an indispensable process.

Table 1
Benefits of using scrap iron and steel

Benefits	Percentage
Savings in energy	74
Savings in virgin materials use	90
Reduction in air pollution	86
Reduction in water use	40
Reduction in water pollution	76
Reduction in mining wastes	97
Reduction in consumer wastes generated	105

Table 2
Recycled materials energy savings over virgin materials

Materials	Energy savings (%)
Aluminum	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60
Paper	64
Plastics	>80

- Upgrading: using mechanical/physical processing and/or metallurgical processing to upgrade desirable materials content, i.e. preparing materials for refining process.
- Refining: in the last stage, recovered materials return to their life cycle.

Consumer electronic equipment (brown goods), such as television sets, radio sets, and video recorders, are most common. However, it is very costly to perform manual dismantling of those products, due to the fact that brown goods contain very low-grade precious metals and copper. A mechanical process is interest for upgrading recycling of WEEE because it can yield full material recovery including plastics. It is expected that a mechanical recycling process will be developed for the upgrading of low metal content scraps.

2. Characteristics of WEEE

Waste electric and electronic equipment is non-homogeneous and complex in terms of materials and components. In order to develop a cost-effective and environmentally friendly recycling system, it is important to identify and quantify valuable materials and hazardous substances, and further, to understand the physical characteristics of this waste stream.

2.1. Hazardous substances and components

WEEE consists of a large number of components of various sizes and shapes, some of which contain hazardous components that need be removed for separate treatment. Major categories of hazardous materials and components of WEEE that have to be selectively treated are shown in Table 3 [1].

2.2. Materials composition

Waste electric and electronic equipment is a complex material containing various fractions. The Association of Plastics Manufactures in Europe (APME) released figures on materials consumption in electric and electronic equipment in western Europe 1995 (Table 4 [5]). In general, printed circuit boards scrap contains approximately 40% metals, 30% plastics, and 30% ceramics [4,6–9].

The main economic driving force for the recycling of electronic scrap is the recovery of precious metals. However, the content of precious metals in WEEE is steadily decreasing [6,10,11].

2.3. Physical characteristics of WEEE

Waste electric and electronic equipment, being a mixture of various materials, can be regarded as a resource of metals, such as copper, aluminum and gold, and plastics. Effective separation of these materials based on the differences on their physical characteristics is the key for developing a mechanical recycling system. Therefore, an in-depth characterization of this specific material stream is imperative.

Table 3
Major hazardous components in waste electric and electronic equipment

Materials and components	Description
Batteries	Heavy metals such as lead, mercury and cadmium are present in batteries
Cathode ray tubes (CRTs)	Lead in the cone glass and fluorescent coating cover the inside of panel glass
Mercury containing components, such as switches	Mercury is used in thermostats, sensors, relays and switches (e.g. on printed circuit boards and in measuring equipment and discharge lamps); it is also used in medical equipment, data transmission, telecommunication, and mobile phones
Asbestos waste	Asbestos waste has to be treated selectively
Toner cartridges, liquid and pasty, as well as color toner	Toner and toner cartridges have to be removed from any separately collected WEEE
Printed circuit boards	In printed circuit boards, cadmium occurs in certain components, such as SMD chip resistors, infrared detectors and semiconductors
Polychlorinated biphenyl (PCB) containing capacitors	PCB-containing capacitors have to be removed for safe destruction
Liquid crystal displays (LCDs)	LCDs of a surface greater them 100 cm^2 have to be removed from WEEE
Plastics containing halogenated flame retardants	During incineration/combustion of the plastics halogenated flame retardants can produce toxic components
Equipment containing CRC HCFC or HFCs	CFCs present in the foam and the refrigerating circuit must be properly extracted and destroyed; HCFC or CFCs present in the foam and refrigerating circuit must be properly extracted and destroyed or recycled
Gas discharge lamps	Mercury has to be removed

2.3.1. Magnetic, density and electric conductivity properties

The magnetic susceptibilities, density, and electric conductivity of some materials used in electric and electronic equipment are given in Tables 5–7 [12–14].

2.3.2. Particle size, shape and liberation properties

Particle size, shape and liberation degree play crucial roles in mechanical recycling processes. Almost all the mechanical recycling processes have a certain effective size range.

Table 4
Main materials found in EEE

Material	Percentage
Ferrous	38
Non-ferrous	28
Plastics	19
Glass	4
Wood	1
Other	10

Table 5
Magnetic susceptibilities of copper alloys used in EEE (data basis: magnetic field intensity, 325 kA/m)

Materials	Fe content (%)	Mass susceptibility, χ ($\times 10^{-7}$ m^3 kg^{-1})
Aluminum-multi-compound bronze	2–4	6.5–11.5
Manganese-multi-compound bronze	1.5–3	0.7–2.4
Special brass	0.7–1.2	1.3–5.8
Brass (Fe-free)	$<$0.2	$<$0.1
Tin and lead bronze	$<$0.2	$<$0.1

Table 6
Magnetic susceptibility, density and electric conductivity of metals used in EEE

Materials	Density, ρ ($\times 10^3$ kg m^{-3})	Electric conductivity, σ ($\times 10^6$ m^{-1} Ω^{-1})
Copper	8.93	59.0
Cu–Zn alloy (Ms 58)	8.4	1.9
Aluminum	2.70	35.0
Magnesium	1.74	23.0
Silver	10.49	68.0
Zinc	6.92	17.4
Gold	19.32	41.0
Brass (Fe-free)	8.40	15.0–26.0
Nickel	8.90	12.5
Tin	7.29	8.8
Lead	11.34	5.0
Alloy steel	7.7	0.7

Characterization of personal computers (PC) scrap and printed circuit boards (PCB) scrap shows, after secondary shredding by a laboratory scale hammer mill, that the main metals present are in the −5 mm fraction for both PC and PCB scrap and show excellent liberation (ca. 99% [6]). Additionally, industry scale tests showed that after two stages comminution, the liberation of −5 mm fraction is between 96.5 and 99.5% [15].

Fig. 1 shows the metal distribution as a function of size range for PC scrap [6]. In this figure, we can see that aluminum is mainly distributed in the coarse fractions (+6.7 mm),

Table 7
Volume resistivity and specific gravity of plastics used in EEE

Plastics	Volume resistivity, Ω m	Specific gravity ($\times 10^3$ kg m^{-3})
Polyvinyl chloride (PVC)	10^9–2×10^{12}	1.16–1.38
Polyethylene (PE)	10^{14}	0.91–0.96
Acrylonitrile butadienestyrene (ABS)	10^{14}	1.04
Polystyrene (PS)	10^{14}	1.04
Polypropylene (PP)	10^{15}	0.90
Nylon and polyamide (PA)	10^{12}	1.14
Ployesters (PET and PBT)	1–1.4×10^{13}	1.31–1.39
Polycarbonates (PC)	8.2×10^{14}	1.22
Elastomer (neoprene, SBR, silicone etc.)	10^9–10^{15}	0.85–1.25

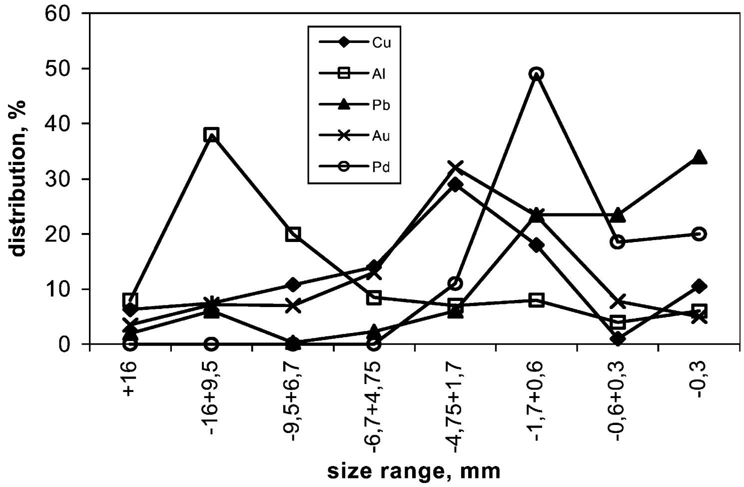

Fig. 1. Metals distribution as a function of size range for PC scrap.

but other metals are mainly distributed in the fine fractions (−5 mm). To know particle size properties is essential for choosing an effective separation technique. In addition, it is common to upgrade metals content by a screening process.

It is well known that diversified particle shapes have a significant impact on material processing, both comminution and separation. On the other hand, differences in particle shape have been utilized in shape sorting technique.

Koyanaka et al. investigated the particle shape properties of copper milled by a swing-hammer-type impact mill [16]. Copper plate and PCB scrap were used as samples. The effects of mill operating conditions, i.e. hammer circumferential speed (v_c) and screen aperture size (diameter, d_s), on shape and size distribution of milled products were examined.

Fig. 2 shows the effect of hammer circumferential speed on anisometry KI and space filling factor ϕ_c of milled copper plate ($d_s = 1$ mm). KI and ϕ_c were defined by the following

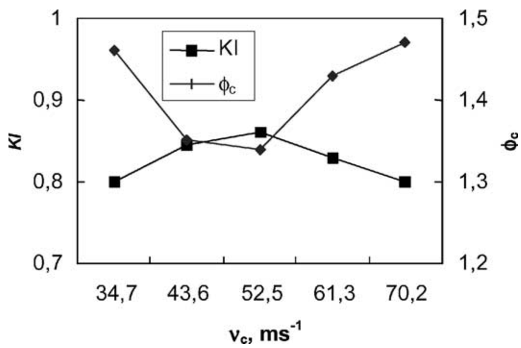

Fig. 2. Anisometry KI and space filling factor ϕ_c of milled copper plate.

equations:

$$\mathrm{KI} = \frac{A}{B}(\leq 1) \tag{1}$$

$$\phi_{\mathrm{c}} = \frac{\pi D^2}{4\mathrm{s}} \tag{2}$$

where A and B are the short and long principal axes of an ellipse of inertia equivalent to particle projection, D the maximum diameter in particle projection, and s the projected area of the particle.

In Fig. 2, it is apparent that hammer circumferential speed influences the particle shape of milled copper. At the same time, the effects of milling conditions on the separation efficiency between copper and non-copper components of PCB scrap using an inclined vibrated plate (IVP) were also studied.

3. Disassembly of WEEE

Disassembly is a systematic approach that allows removal of a component or a part, or a group of parts or a subassembly from a product (i.e. partial disassembly); or separating a product into all of its parts (i.e. complete disassembly) for a given purpose [17].

The areas of disassembly that are being pursued by researchers are focused on disassembly process planning (DPP) and innovation of disassembly facilities.

3.1. Disassembly process planning

The objective of disassembly process planning is to develop, procedures and software tools for forming disassembly strategies and configuring disassembly systems [18]. The following phases for developing a disassembly process plan have been proposed [17–23]:

- Input and output product analysis: In this phase, reusable, valuable, and hazardous components and materials are defined. After preliminary cost analysis, optimal disassembly is identified.
- Assembly analysis: In the second phase, joining elements, component hierarchy and former assembly sequences are analyzed.
- Uncertainty issues analysis: Uncertainty of disassembly comes from defective parts or joints in the incoming product, upgrading/downgrading of the product during consumer use, and disassembly damage.
- Determination of dismantling strategy: In the final phase, it is decided whether to use non-destructive or destructive disassembly.

Research on disassembly process planning has been an active area in the last decade. Hundreds of papers have been written on this subject. A detailed survey of disassembly was presented by Gungor and Gupta [19].

3.2. Innovations of disassembly tools

In addition to generating a good disassembly process plan, the implementation of disassembly needs highly efficient and flexible tools. Several patented disassembly tools were highlighted in the paper by Feldmann et al. [24].

The most attractive research on disassembly process is the use of robots. The automated assembly of electronic equipment is well advanced. Unfortunately, full (semi) application of automation disassembly for recycling of electronic equipment is full of frustration. Currently, there are only a few pilot projects for automated disassembly of keyboards, monitors and printed circuit board, and there is no (semi-) automated solution for the PC itself [25,26].

3.3. Disassembly in practice

In the practice of recycling of waste electric and electronic equipment, selective disassembly (dismantling) is an indispensable process since: (1) the reuse of components has first priority, (2) dismantling the hazardous components is essential, (3) it is also common to dismantle highly valuable components and high grade materials such as printed circuit boards, cables, and engineering plastics in order to simplify the subsequent recovery of materials.

Most of the recycle plants utilize manual dismantling. Ragn-Sells Elektronikåtervinning AB in Sweden is a typical electronics recycling operation. Fig. 3 illustrates the current disassembly process that they utilize [27]. A variety of tools is involved in the dismantling process for removing hazardous components and recovery of reusable or valuable components and materials.

A study of potential future disassembly and recycling technologies for the electronics and the automotive industry was carried out by Boks and Tempelman between November 1996 and March 1997 [28]. The results reflect the opinions of a panel of approximately 70 specialists pre-selected by the authors. Concerning the technical feasibility of full automation

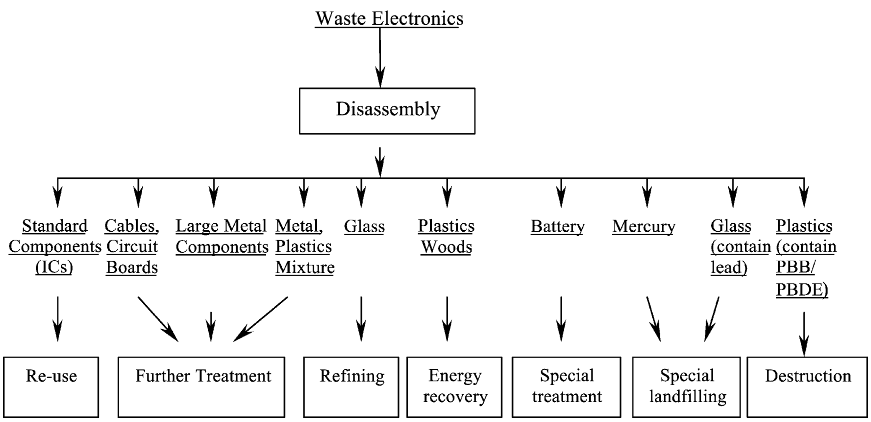

Fig. 3. Recycling process developed by Ragn-Sells Elektronikåtervinning AB.

(90–100%) disassembly of electronic equipment, 65% of the panel members thought a breakthrough in automated disassembly will occur by 2010; and 57% of the panel thought it will be in Germany, while only 35% of the German panel members agree. In addition, 32% of the panel thought full automation disassembly of both brown goods (e.g. TVs, audio and video equipment) and white goods (e.g. freezers, washing machines) will not be economically attractive by 2020. In their opinion, the main obstacles preventing automated disassembly from becoming a commercially successful activity are: (1) too many different types of products, (2) the amount of products of the same type is small, (3) general disassembly-unfriendly product design, (4) general problems in return logistics and (5) variations in returned amounts of products to be disassembled.

Fortunately, research in the field of product design for disassembly has gained momentum in the past decade. One good idea is self-disassembly which is called active disassembly using smart materials (ADSM). Chiodo [29] reported the application of shape memory polymer (SMP) technology to the active disassembly of modern mobile phones. The smart material SMP of polyurethane (PU) composition was employed in the experiments. This method provides a potential dismantling scenario for the removal of all components if this material was to be developed for surface mount components. Research into using ADSM in other small electronics also has been done to handle units such as telephones, cell phones, PCB/component assemblies, cameras, battery chargers, photocopier cartridges, CRTs, computer casings, mice, keyboards, game machines and stereo equipment [29].

4. Mechanical/physical recycling process

4.1. Screening

Screening has not only been utilized to prepare a uniformly sized feed to certain mechanical process, but also to upgrade metals contents. Screening is necessary because the particle size and shape properties of metals are different from that of plastics and ceramics.

The primary method of screening in metals recovery uses the rotating screen, or trommel, a unit which is widely used in both automobile scrap and municipal solid waste processing. This unit has a high resistance to blinding, which is important with the diverse array of particle shapes and sizes encountered in waste. Vibratory screening is also commonly used, in particular at non-ferrous recovery sites, but wire blinding is a marked problem [30].

4.2. Shape separation

Shape separation techniques have been mainly developed to control properties of particles in the powder industry [31–34]. The separation methods were classified into four groups by Furuuchi [31]. The principles underlying this process makes use of the difference: (1) the particle velocity on a tilted solid wall, (2) the time the particles take to pass through a mesh aperture, (3) the particle's cohesive force to a solid wall, and (4) the particle settling velocity in a liquid.

Shape separation by tilted plate and sieves is the most basic method that has been used in recycling industry [17,35]. An inclined conveyor and inclined vibrating plate were used as a particle shape separator to recover copper from electric cable waste [35], printed circuit board scrap [17], and waste television and personal computers in Japan [36].

4.3. Magnetic separation

Magnetic separators, in particular, low-intensity drum separators are widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes. Over the past decade, there have been many advances in the design and operation of high-intensity magnetic separators, mainly as a result of the introduction of rare earth alloy permanent magnets capable of providing very high field strengths and gradients.

In Table 5, we can see that the use of high-intensity separators makes it possible to separate copper alloys from the waste matrix. An intense field magnetic separation is achievable at least for the following three alloy groups [14]:

- copper alloys with relatively high mass susceptibility (Al multi-compound bronze);
- copper alloys with medium mass susceptibility (Mn multi-compound bronze, special brass);
- copper alloys with low mass susceptibility and/or diamagnetic material behavior (Sn and Sn multi-compound bronze, Pb and Pb multi-compound bronze, brass with low Fe content).

4.4. Electric conductivity-based separation

Electric conductivity-based separation separates materials of different electric conductivity (or resistivity) (Tables 6 and 7). As shown in Table 8, there are three typical electric conductivity-based separation techniques: (1) Eddy current separation, (2) corona electrostatic separation, and (3) triboelectric separation [37–41].

In the past decade, one of the most significant developments in the recycling industry was the introduction of Eddy current separators whose operability is based on the use of rare earth permanent magnets. The separators were initially developed to recover non-ferrous metals from shredded automobile scrap or for treatment of municipal solid waste [30,42–44], but is now widely used for other purposes including foundry casting sand, polyester polyethylene terephthalate (PET), electronic scrap, glass cullet, shredder fluff, and spent potliner [45–50]. Currently, Eddy current separators are almost exclusively used for waste reclamation where they are particularly suited to handling the relatively coarse sized feeds.

The rotor-type electrostatic separator, using corona charging, is utilized to separate raw materials into conductive and non-conductive fractions. The extreme difference in the electric conductivity or specific electric resistance between metals and non-metals supplies an excellent condition for the successful implementation of a corona electrostatic separation in recycling of waste. To date, electrostatic separation has been mainly utilized for

Table 8
Mechanical separation processes based on electric characteristics of materials

Processes	Separation criteria	Principles of separation	Sorting task	Workable particle size ranges
Eddy current separation	Electric conductivity and density	Repulsive forces exerted in the electricly conductive particles due to the interaction between the alternative magnetic field and the Eddy currents induces by the magnetic field (Lorentz force)	Non-ferrous metal/non-metal separation	>5 mm
Corona electrostatic separation	Electric conductivity	Corona charge and differentiated discharge lead to different charges of particles and this to action of different forces (particularly, image forces)	Metal/non-metal separation	0.1–5 mm (10 mm for laminar particles)
Triboelectric separation	Dielectric constant	Tribo-charge with different charges (+ or −) of the components cause different force directions	Separation of plastics (non-conductors)	<5 (10) mm

the recovery of copper or aluminum from chopped electric wires and cables [37,38,51–54], more specifically the recovery of copper and precious metals from printed circuit board scrap [37–39,55].

Triboelectric separation makes it is possible to sort plastics depending on the difference in their electric properties (Table 7). For the processing of plastics waste, research has shown many obvious advantages of triboelectric electrostatic separation, such as independence of particle shape, low energy consumption, and high throughput [41].

4.5. Density-based separation

Several different methods are employed to separate heavier materials from lighter ones. The difference in density of the components is the basis of separation. Table 9 shows that density-based separation processes have found widespread application in non-metal/metal separation [56].

Gravity concentration separates materials of different specific gravity by their relative movement in response to the force of gravity and one or more other forces, the latter often being the resistance to motion offered by a fluid, such as water or air [57]. The motion of a particle in a fluid is dependent not only on the particle's density, but also on its size and shape, large particles being affected more than smaller ones. In practice, close size control of feeds to gravity processes is required in order to reduce the size effect and make the relative motion of the particle specific gravity dependent.

Table 9
Density separation processes utilized for non-metal/metal separation

Density separation process	Workable piece sizes (mm)	Utilized for following sorting tasks					
		Plastics waste	Aluminum scrap	Lead battery scrap	Cable scrap	Electronic scrap	Light steel scrap
Sink-float separation							
In liquids		+		+	+		+
In heavy media							
Gravity separator	5–150		+	+		+	+
Hydrocyclone	<50						+
In aerosuspensions							
In aero-chutes	0.7–3				+		
In fluidized bed trough separators	0.7–5				+		
Sorting by jigging							
Hydraulic jigs	2–20						+
Pneumatic jigs	<3				+		
Sorting in chutes and on tables							
Aero-chutes	0.6–2				+		
Aero-tables	<4				+		
Up-stream separation							
Up-stream hydraulic separation	5–150	+		+			+
Up-stream pneumatic separation	<300				+		

5. Mechanical recycling process for fine particles

The number of waste streams containing fine metal particles is foreseen to grow substantially in the near future [59], due to: (1) more stringent legislation, (2) more costly landfilling for metal-containing waste, (3) continuing increased production of diversified waste streams, particularly the arising of portable EEE, and (4) ever-growing environmental awareness. It is predicted that an economic and technically viable separation technology to recover fine particles from waste will be in great demand in the near future.

5.1. New developments of the ECS for small particles

The rotating Eddy current separators have been successfully utilized in several non-ferrous metals sorting and recovery operations, most common is the sorting of non-ferrous metals from shredded automobile scrap and municipal solid waste [42,58,60]. Nevertheless, in recycling of WEEE, the use of the traditional Eddy current separator is limited, due to the size of feed required. Particles greater than 5 mm in size or, even 10 mm are needed [61].

In recent years, there have been some development of Eddy current separation processes designed to separate small particles [44,59–64]. Understanding the interaction between the separator field and conductive particles is essential to provide a theoretical foundation for this novel design.

Before the 1990s, intensive theoretical work was carried out by Schlömann [65,66] and van der Valk et al. [56,67,68]. A theoretical model was developed to calculate the magnitude of the forces exerted on small block-shaped particles in magnetic fields with periodical variations. The separators involved in the study were ramp Eddy-current separator (RECS), vertical Eddy-current separator (VECS), and rotating disc separator (RDS). This model has been used to design separators with different field distributions and mechanical constructions. The validity of this model was tested by deflection measurements in a VECS and by force measurements in two different RDS prototypes. The deflection measurements were carried out with copper particles extracted from granulated power cables. These particles are pieces of wire with diameters between 0.2 and 4 mm and with lengths mainly between 3 and 10 mm. The particles sizes by screening and calculation correspond with each other, as the size range does not exceed 3 mm.

In the early 1990s, theoretical work was done by Fletcher et al. [63,69–72]. In these studies, three kinds of theoretical models were used to represent the profile of the magnetic field at the boundary of a single boundary Eddy current separator. In the first model, the magnetic field profile at the boundary of ECS was represented by an idealized single field step of height ΔB_z, which equals the flux density change between the point of element velocity measurement and the point where maximum flux density is first reached. This model is satisfactory for large conductors with medium v_y (velocity of particle in y-axis direction). In the second model, a multi-step staircase field that follows the measured profile was used for representing the magnetic field of ECS. This model was presented in paper [71]. The last model was developed for small conducting particles. A single rising linear ramp was used as a theoretical representation of the profile of the magnetic field at the boundary of a single boundary ECS. Fletcher et al. [63] discussed the limitations of single boundary ECS for small particles. A theoretical model was developed and tested using a bench top single boundary ECS. Two sizes of aluminum laminar discs with 5.1 mm × 2 mm and 10.2 mm × 1.5 mm were used in the test. The results of this model were reasonably consistent with experimental observation. In addition, Fletcher predicted that if a 2T ramp of length 10 mm was possible and was used with a deep-set splitter, the limit of particle size is reduced to 0.6 mm.

An important work involving the separation of small particles using the ECS method was carried out by Rem and co-workers [59–62,73,74]. A model was developed for small and medium-sized particles in both symmetric and asymmetric fields by treating the particles as magnetic dipoles. The theory was expanded in Rem's paper [60] for a rotary drum separator, sliding ramp, and vertical Eddy current separator. Zhang et al. [61] presented the results of their investigation of the separability of various materials smaller than 5 mm using a rotating type ECS. The study shows that the magnetic drum should rotate backwards for sorting small non-ferrous metal particles. They concluded that the "backward phenomenon" results from the competition between the tangential Eddy current force and the dynamic frictional force crested by the electromagnetic torque.

Based on the analysis of separation mechanisms, proposals were made to improve the separation selectivity of small particles. A number of novel design concepts of ECS were highlighted by Rem et al. [59]. The redesigned Delft vertical ECS (VECS), the prototype

TNO ECS and a laboratory wet ECS (WECS) were used in their investigation. The new VECS was redesigned based on the one developed by van der Valk et al. [68]. In this study, the magnets were more powerful than the ones used earlier. The separation results of binary mixtures by Delft VECS were presented in the article.

The prototype designed by The Netherlands Organization (TNO for Applied Scientific Research) combines a small pole width of approximately 20 mm with a narrow gap between magnet surface and feed, and a high rotor speed of up to 4000 rpm. Theoretical analysis showed that the tangential Eddy current force of TNO ECS is six times that of the rotary belted-drum ECS. The idea of a wet ECS comes from converting the effects of the electromagnetic torque to a separating effect. It is well known that a spinning particle moving through a fluid experiences a force perpendicular both to its direction of motion and to the axis of rotation. This is the Magnus effect. The experimental results of WECS have shown to be promising. A critical comparison of the four types ECS was given by Rem et al. [59] (Table 10).

Norrgran [44] discussed the application of an Eriez rotating belted-drum ECS in the beneficiation of fine sized metals, such as aluminum slags, brass foundry sands, and electronic scrap. Typical customer applications that have resulted in effective separations are given in his article (Table 11).

A vertical Eddy current rotating separator, designed to increase the separation efficiency and to reduce the cost of the separation equipment, was proposed by Schlett et al. [64]. In the separator, the magnetic drum with NeFeB permanent magnets was driven by a dc electric motor that was placed under the magnetic drum. A mixture of copper wire and plastic particles with the average diameter of 4 mm and length of 5 mm was used to simulate electronic wastes in a laboratory-scale experiment.

5.2. Corona electrostatic separation

Corona electrostatic separation is an important technique suitable for fine particles with the size range of 0.1–5 mm [37–39]. This process has been investigated extensively in the minerals processing industry. There are also some applications in recycling of cable scraps. The utilization of corona electrostatic separators in material recovery from waste electric and electronic equipment for a recycling purpose is only in its infancy. Some industrial applications for the corona drum separator are shown in Table 12 [75].

In corona electrostatic separation, electrode system, rotor speed, moisture content, and particle size have the greatest effect in determining the separation results. Both fundamental and practical aspects concerning the design of new electrode system have been investigated and developed by Iuga et al. [51–53,76]. An experimental study was carried out on the influence of material superficial moisture on insulation-metal electrostatic separation [54].

Comparing the foregoing processes with the mineral processing industry processes, one finds that larger liberated particles with 5–8 mm are usually encountered in recycling of WEEE, although they are generally called fine particles. In electrostatic separation, coarse particles collect small specific charges and hence small electric forces, while having relatively large centrifugal forces. Optimization of the electrode system, enhancing electrode

Table 10
Critical comparison of ECS with various design concepts for small particles

Design concept	Throughput	Separation selectivity	Operating difficulty (sensitivity to the magnetics)	Maintenance	Number of non-ferrous products at one step	Investment cost for 1 t/h	Final results
Dry							
Rotating drum type	++	+	0	0	0	0	+++
VECS	0	0	−	+	−	−	−
TNO ECS	+	++	−	−	0	+	++
Wet							
Rotating drum WECS	+	+++	+	−	+	−	++++

Note that “0”, “−”, and “+” denote base, negative and positive, respectively.

Table 11
Typical applications of the Eddy current separator in waste treatment industry

Sample description	Feed rate, tph[a]	Weight percent of feed (%)		
		Magnetics	Conductor	Non-conductor
Aluminum cans and PET bottles	1	–	49	51
Shredded PET bottles and aluminum caps	1	–	2	98
Mixed aluminum and PVC	1	–	33	67
Auto scrap (unscreened)	3	60	33	7
Auto scrap (7 × 1/2 in.)	3	30	35	35
Auto scrap (−1/2 in.)	3	27	24	49
Mixed ferrous and non-ferrous scrap (−3/4 in.)	3	53	43	4
RDF bottom ash (3 × 5/8 in.)	6	3	3	94
RDF bottom ash (−5/8 in.)	3	10	3	87
Glass cullet with aluminum caps	3	1	9	90
Glass cullet (crushed light bulbs)	1	4	14	82
Electronic scrap, coarse	2	5	48	47
Electronic scrap, fine	1	67	14	19
Mixed Fe, Al, Zn	4	10	55	35
Mixed Fe, Al, Cu, Pb, Zn	6	28	30	42
Brass foundry casting sand	3	–	12	88
Aluminum foundry casting sand	6	–	5	95
High grade aluminum slag	3	7	81	12
Low grade aluminum slags	1	2	5	93
Aluminum dross and cryolite	4	–	26	74

[a] Unit capacity of tph/ft of rotor width.

Table 12
Applications of the corona drum separator in waste treatment industry

Materials	Waste origin	Liberation method	Particle size	Achievable grades of products	Remarks
Cu PVC/PE	Cable scrap	Cutting mill	0.5/5 mm	Cu 90–99% Plastics up to 99%	
Al PS	Skeleton waste e.g. milk cans	Cutting mill	6/12 mm	Al up to 100% PS 99%	
Al Plastics	Compound materials e.g. tetra brick	Cryogenic grinding	50/500 μm	Al 95% Plastics 95%	
Cu Epoxy resin	Bare PC boards	Hammer mill	0.2/2 mm	Cu 99% Resin 99.5%	
PE EOVH	Car tanks	Cutting mill	3/5 mm	PE 95% EVOH 90%	Separation of non-conductor

voltage, and lowering down the rotor speed can maximize the adhering of non-conductive particles.

One of the advantages of electrostatic separation in cable recycling is to obtain a metal-free product. However, in some cases, the specific resistance of certain types of flexible PVC and rubber used to make cables falls below $4 \times 10^{10}\ \Omega$ m. Hence, corona electrostatic separation is difficult because the discharge time constant of the non-conductor may fall below 1 s [37].

5.3. Jigging

Jigging, one of the oldest methods of gravity concentrations, is widely utilized in the mineral processing industry to concentrate relatively coarse materials. If the feed is fairly uniformly sized (e.g. 3–10 mm), it is not difficult to achieve good separation of a narrow specific gravity range in minerals in the feed [57].

Thus, the jigging process provides a good solution for sorting small pieces of metals by density separation. Advantages of wet jigs are their robustness, high capacity per unit surface, low operating costs and suitability to process large amounts of small particles. According to de Jong and Dalmijin [77], in the processing of car scrap, the 4–16 mm non-ferrous fraction can be separated by wet jigging. The light product mainly consists of aluminum, glass, and stone; the heavy product consists of metals, such as copper, lead, brass, and stainless steel etc. A recyclable intermediate fraction, continuously added to the feed of the jig was introduced to on-screen jigging. In this study, the principles of jigging and of the intermediate layer are discussed first. Then the optimum properties of the intermediate layer and metal distribution in the jig bed are described.

One of the important applications of the jig in recycling industry is separation of light and heavy products in recycling demolition rubble. Wet jigging enables a high-grade heavy product to be achieved. Plant-scale testes were carried out at Groot B.V., a Dutch company in Heilo The Netherlands. The test was designed to reduce the light product content of the recycle stream to at least a maximum of 0.1% by weight [78]. A pulsator jig was used in the study. The results show that wet processing of demolition rubble with a pulsator jig enables a product quality not possible with air classifiers to be achieved.

Before the 1990s, this process had also been utilized for sorting of non-ferrous metals pro-concentrated of light steel scrap processing (hydraulic jigs) and from cable scrap (pneumatic jigs). Recently, Schmelzer [79] discussed the separation of non-ferrous metal

Table 13
Mass recovery and density composition of light and heavy product fractions of jig process treating non-ferrous metal mixtures

Size fraction (mm)	Product	Recovery (%)	Density distribution of products (g/cm^3)				
			<2.4	2.4–2.7	2.7–3.0	3.0–3.3	>3.3
10–4	Light	75.3	48.4	51.6	–	–	–
	Heavy	24.7	–	–	0.2	0.9	98.9
4–0.5	Light	76.7	42.1	56.1	1.8	–	–97.9
	Heavy	13.3	–	–	1.0	1.1	

mixtures with particle size ranges of 4–10 and 0.5–4 mm, using a discontinuous U-tube jig. Table 13 shows the separation results.

Significant heterogeneity and high complexity of WEEE make it difficult to operate a jigging process. Complicated scrap pieces, particularly wiry materials impede the separation process considerably and can prevent a separation into layers [56].

6. Conclusions

(1) Waste electric and electronic equipment has been taken into consideration not only by the government but also by the public. With the climate change being of concern, mechanical/physical processing will play an essential role in upgrading of WEEE.
(2) Characterization of WEEE provides a sound and solid foundation for developing effective separation techniques. However, WEEE is significantly heterogeneous and complex in terms of the type, size, and shape of components and materials. Therefore, an in-depth study should be done with a goal of clearly understanding this special waste stream.
(3) In order to be separated, WEEE must be shredded to small even fine-sized particles, usually below 10 mm or even 5 mm. Mechanical separation of fine particles is needed in the recycling of WEEE.
(4) Eddy current separation, corona electrostatic separation, and jigging are three important processes that have been developed in recycling of automobile scrap, waste cables, and building materials, respectively. For sorting fine WEEE, the foregoing also provide alternative approaches to current systems.
(5) In recycling of WEEE, investigations to date have mainly focused on the recovery of precious metals from personal computer scrap and printed circuit boards scrap. However, it is important that recycling of the electronic scrap that contains very low-grade precious metals, such as brown goods, should be investigated.

Acknowledgements

The authors are grateful for financial support and approval of publication for this paper from the Minerals and Metals Recycling Research Center (MiMeR), Sweden.

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