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Eddy current separation for recovery of non-ferrous metallic particles: A comprehensive review

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ABSTRACT

Eddy current separation (ECS) is a process used throughout the scrap recycling industry for sorting nonferrous metals from other nonmetallic fluff. The mechanism is based on the principle that a time-varying magnetic field will induce electrical current to flow throughout the body of a conductive particle. This current then reacts to the applied magnetic field by exhibiting a pronounced force of deflection, thereby separating the materials. The process is remarkably efficient and environmentally friendly, making it essential to the growth and sustainability of the metal recycling industry. In this review, we aim to summarize the available literature on eddy current separators for recovery of nonferrous metals. Although several different designs of eddy current separators have been examined through the years, the most common in use today remains the belt-driven rotary drum design. Limitations of the belt-driven rotary drum design are discussed as well as potential new designs and new applications for eddy current separators.

1. Introduction

Metals play an integral role in modern society. In 2017 alone, the apparent U.S. consumption of iron and steel reached 100 million metric tons (USGS, 2018). Aluminum consumption likewise reached almost six million metric tons, with copper following at 1.85 million metric tons (USGS, 2018). Unfortunately, the mining and processing of such metals can have large environmental impacts if not managed properly, such as destruction of native landscapes, acid mine drainage/wastewater treatment, and gaseous and particulate emissions. Increasing consumer demand also contributes heavily to increasing environmental impacts. Relative to production rates in the 1900s, six out of 11 of the most commonly recovered metals are now produced at rates of 10 or even 1000 times more (Johnson et al., 2007). To compound the problem even further, the ore grade of most operational mines has been steadily degrading over time. For example, the global average ore grade of copper has decreased from 1.1 wt% in the 1970s to about 0.8 wt% in 2009 (Crowson, 2012). Thus, to maintain consistent production levels, a larger amount of material must be mined and processed accordingly, which only results in further environmental impacts (Norgate and Haque, 2010; Norgate and Jahanshahi, 2010).

With the depletion of high-grade ores and an increasing global demand, we are faced with two possible solutions: (1) improve our current extraction methods of low-grade virgin ore deposits, or (2) develop and integrate new recycling technologies within the existing value chain. Due to the relative technological maturity of the mining industry, however, the first solution is likely to expect only incremental improvements in the foreseeable future. In contrast, recycling is a comparatively young industry with tremendous potential for growth and technological innovation. This is also evident from consistent economic growth that the recycling industry has demonstrated. For example, the U.S. metal scrap recycling industry has increased by 37% from $77 billion in 2010 to $106 billion in 2015 (ISRI, 2016). Another strong economic incentive for recycling is a study by Johnson et al. (2007) which found that most metals currently targeted for recycling have post-disassembly concentrations that are more enriched than minimum profitable ore grades. A recent study by Sverdrup et al. (2017) also estimates that scrap will become the main source for iron, aluminum, and copper within the next 30 years.

Of all the materials used in society, metals have the greatest recycling potential. Not only are metals relatively easy to recover from municipal waste, but their physical properties do not degrade over time like other materials (e.g., plastics and paper). Recycling also requires significantly less energy than mining, since materials generally need only to be melted rather than processed from raw mineral deposits. For many common commodity metals (i.e., Al, Cu, Fe and steel), these savings can typically reach as high as 70% or more (Cui and Forssberg, 2003). Due to the high demands of electrolytic reduction, aluminum

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Table 1
Summary table of ten commonly recycled metals in the U.S., their recycled percentage, exports, and imports. Data Source: USGS (2017).

	Percentage recycled	Exports (metric tons)	Imports (metric tons)	Exports/ Imports
Aluminum	47	1,550,000	521,000	2.98
Chromium	35	514,000	192,000	2.68
Copper	33	955,000	112,000	8.53
Iron and steel	49	12,800,000	3,590,000	3.57
Lead	68	46,600	10,100	4.61
Magnesium	51	432	21,300	0.020
Nickel	43	540,000	218,000	2.48
Tin	30	2,530	32,700	0.077
Titanium	63	6,860	22,100	0.31
Zinc	18	55,200	18,000	3.07

recycling can even reach as high 95% energy savings when compared to mining.

Based on U.S. Geological Survey data from 2015, the United States recycled approximately 58.3 Mt of the metals (Table 1), which was equivalent to about 49% of the supply of those metals (USGS, 2017). By percentage, the top three recycled metals were lead, titanium, and magnesium. By mass, however, 90% of the recycled metal was iron and steel. The recycling rates from 2011 to 2015 for the metals in Table 1 are plotted in Fig. 1. Generally speaking, recycling rates in the U.S. have either remained relatively constant or decreased slightly from 2011 to 2015, with the exception of titanium. Only chromium and nickel experienced a noticeable increase in recycling rates from 2014 to 2015. Despite the numerous advantages to metal recycling, the supply of nonferrous metals in the United States tends to vary between 30 and 60% from recycled sources.

1.1. Beneficiation of metal scrap

In order to effectively recycle scrap metal, it must first be separated from other materials (e.g., polymers/plastics, glass, fibrous materials, construction materials, etc.), as well as other dissimilar metals (e.g., ferrous from nonferrous). This process is arguably one of the most important cost barriers to the entire industry, as it depends highly on the availability of technology as well as the composition of a particular stream. Similar to mineral processing, the first step is usually some physical size reduction via chopping, shredding, crushing, etc. After size reduction, various physical separation methods can be used to separate the mixture based on properties of the material. This is accomplished by exploiting differences in physical properties of various materials such as density, magnetism, and electrical conductivity.

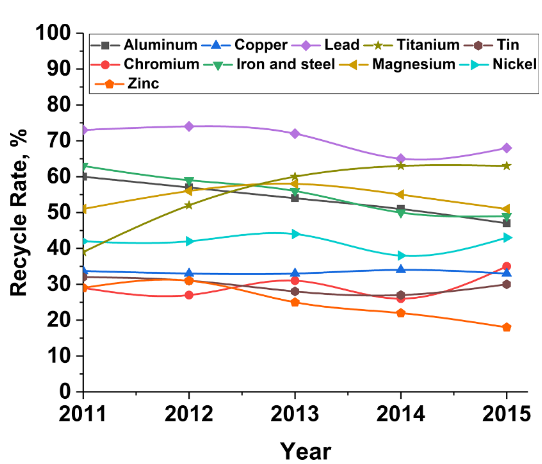

Fig. 1. Recycle rate for ten commonly recycled metals in the U.S. from 2011 to 2015. Data Source: USGS (2017).

A metal shredder plant generally generates three fractions, commonly referred to as the Ferrous, Heavy Fraction (HF), and Light Fraction (LF). The Ferrous mainly consists of iron and steel products, and is separated by magnetic separators after shredding. The HF consists of mainly of nonferrous metals, alloys, and nonmetallic materials. The LF is mainly dirt/fluff with a small metal fraction (less than 5%) and is recovered by screening and air suction.

Automotive Shredder Residue (ASR) is a combination of HF and LF, and annually generates approximately five million tons worldwide, which is about 5% of the global industrial waste (Mallampati et al., 2018). Most of this residue ends up in landfills or is converted thermally (Cossu and Lai, 2015; Nicolli et al., 2012; Simic, 2013). Automotive Shredder Residue consists of a wide variety of materials, including precious metals, plastics, glass, rubber, wood, foam, tramp metal, wire, fibers, sand, and dirt (Cossu and Lai, 2015; Simic, 2013; Widmer et al., 2015). The compositions of these fractions are dynamic and highly dependent on the feed materials. Generally, the Ferrous fraction can be sold directly to steel producers without much further purification/ treatment, whereas the HF requires further purification before it can be sent to metal producers. The LF is often landfilled and has been a topic of research to recover engineered polymers, energy, and metals.

Refining of the HF requires the further use of separation methods/ technologies to acquire an enriched product. Sometimes to achieve a desired quality fraction, even further size reduction may be required. Although nonmetallic materials are generally still within the HF, these can be removed by density separation methods. For smaller particles (< 0.5 mm) in the LF, froth flotation can be utilized to further recover engineered polymers of value.

1.2. Magnetic separation

Ferrous scrap metal is that which contains iron, and is generally removed first is scrap sorting. Examples of some common ferrous metal scrap include alloy steel, carbon steel, cast and wrought iron. It is worth noting that a common misnomer is to associate *ferrous* with *magnetic* and vice versa. Ferromagnetism is a magnetic property, which describes how certain materials form permanent magnets or are attracted to magnets. Examples of ferromagnetic materials include iron, nickel, cobalt, some rare earth oxides, as well as some naturally occurring minerals, e.g., lodestones (magnetite is actually considered ferrimagnetic, which is similar to ferromagnetic). Other types of magnetism include paramagnetism, diamagnetism, and antiferromagnetism, but are generally much weaker effects.

Magnetic separation is a process that extracts ferromagnetic materials through the use of powerful, permanent magnets. The basic principle has been also used since the mid-1800s in mineral processing for removal or tramp iron or iron ore beneficiation. It is also used to remove strongly ferromagnetic impurities from non-metallic ore (e.g. quartz and feldspar). A review by Oberteuffer (1974) covers the of principles, devices, and applications of magnetic separation. Although magnetic separators utilize magnetic properties to separate materials, they do not work particularly well with weakly magnetic or non-ferromagnetic metals. For example, aluminum and titanium are nonferrous metals that are technically magnetic. However, they do not have strong innate magnetic moments, and thus a different separation mechanism is required.

1.3. Eddy current separation

After magnetic separation has removed the bulk ferrous fraction from a scrap material stream, the most common processing step to occur next is eddy current separation (ECS). The mechanism works by exposing conductive, nonferrous particles to a time-varying magnetic field, which in turn gives rise to electrical currents throughout their volumes (Schloemann and Reiner, 1979). The relative motion between the current and the magnetic field gives rise to a force, called the

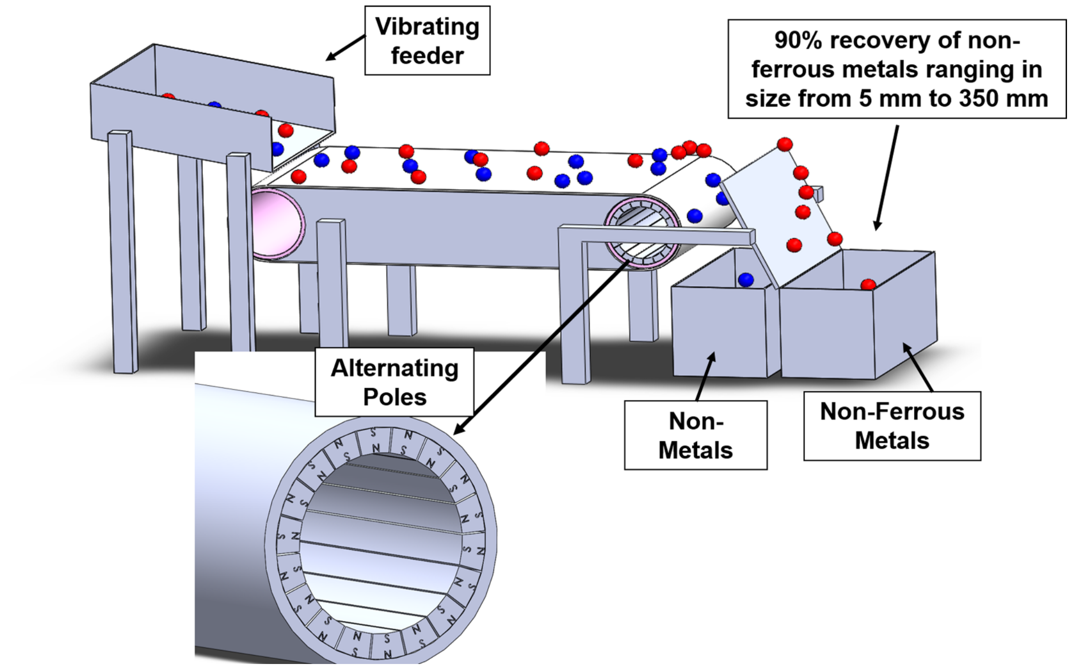

Fig. 2. Depiction of a typical belt-driven rotary drum design of an eddy current separator.

Lorentz force, which subsequently deflects the nonferrous scrap particles away from the nonmetallic fluff. A Lorentz force is the combination of electric and magnetic force on a particle due to electromagnetic fields.

In most commercial designs, the time-varying magnetic field is achieved by rotating a cylindrical array of permanent magnets with alternating polarity (Fig. 2). If the magnetic array is both strong enough and fast enough, metallic particles will actually lift off the feed belt and hurl over the mechanical splitter nearby. The process tends to work well at extracting particles of aluminum, copper, brass, and zinc, and can even do so with a throughput of many tons per hour. In contrast, the attractive forces on ferrous materials are usually much stronger than the repulsive Lorentz forces, which is why magnetic separation is a common pre-processing step that always occurs before ECS.

The application of ECS technology offers a robust method to separate a nonferrous fraction with high recovery; however, existing ECS designs are limited by particle geometry. Although eddy current phenomenon was discovered well over a hundred years ago and is used in the design of electric motors, dynamos, and transformers, for example, there still exist knowledge gaps in the fundamental understanding of eddy currents. In regards to eddy-current separators, many developments and U.S. patents were granted in the 1960s. Further developments where contributed by Schloemann, Forssberg, Rem, and Zhang from the late 1970s to the 1990s. Eddy current separation has historically been overlooked as a means of separating nonferrous metals from a mixture of other materials. The designs of these separators have only made incremental advancements in metal fraction separations, while new designs of eddy current separators are stagnant. This is a result of a technical understanding of the separation mechanism. The available literature on the subject is still in development. Reviews on the technical applications of eddy current separators have been published by Schloemann (1979,1982) and more recently by Jujun et al. (2014) and Wang et al. (2013). However, the number of extensive and critical reviews on this topic is limited to date.

2. Theory of eddy current separation

Although the basic principle of eddy current separation has been well known for decades, the underlying theory that governs it is notoriously complex. An excellent text to review the formulation of electromagnetic fields in materials is that by Jackson (1999). Broadly speaking, the process begins with a time-varying magnetic field intensity $\mathbf{B}(\mathbf{r},t)$, where $\mathbf{r}$ is an arbitrary position vector and t is time. According to Faraday's law, the time-variation on $\mathbf{B}$ gives rise to an electric field $\mathbf{E}$ in accordance with

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{1}$$

In practice, it is almost always appropriate to assume that the system is operating in a sinusoidal steady state with angular frequency ω; or if not, then it can at least be expressed as a superposition of sinusoidal steady states over a spectrum of many distinct frequencies. In either case, the time derivative is typically replaced with $\frac{d}{dt} = j\omega$, where $j = \sqrt{-1}$ is the imaginary unit. We may then express Faraday's law in phasor form as

$$\nabla \times \mathbf{E} = -j\omega\mathbf{B} \tag{2}$$

When a conductive particle like aluminum or copper is placed somewhere inside of $\mathbf{E}$, Ohm's law dictates that an electric current density $\mathbf{J}$ must arise in accordance with

$$\mathbf{J} = \sigma\mathbf{E} \tag{3}$$

where σ is called the electrical conductivity of the particle. In turn, the induced current density $\mathbf{J}$ then gives rise its own time-varying magnetic field $\mathbf{B}_e$, called the eddy magnetic field, or the induced magnetic field. The relationship between $\mathbf{J}$ and $\mathbf{B}_e$ follows the quasistatic form of Ampere's law, written as

$$\nabla \times \mathbf{B}_e = \mu_0\mathbf{J} \tag{4}$$

where μ_0 is the magnetic permeability of free space. Note that we are specifically neglecting any contributions due to the displacement current $\partial\mathbf{D}/\partial t$, which is only relevant when radio waves are carrying away significant amounts of energy in the form of electromagnetic radiation. This generally does not occur unless the geometry of interest is at least one-tenth of a wavelength in size, thus implying a frequency on the order of several MHz for typical eddy current separators.

The greatest mathematical complication arises from the fact that $\mathbf{B}_e$ also creates its own electric field $\mathbf{E}$ in accordance with (Eq. (2)) and thus its own current density **J**. Consequently, it is not an easy matter to simply derive for **J** under some magnetic field excitation **B**. Instead, both **J** and $\mathbf{B}_e$ must be solved for simultaneously. Depending on the specific geometry of interest, however, there can be many different ways to go about this task. (Nagel, 2018b), provides a detailed exploration of this process and solves for **J** under basic shapes like cylinders and spheres.

Once a solution for **J** has been found, the next step is to calculate the net, time-averaged force acting on it. This is accomplished by applying the magnetic force law,

$$\mathbf{F}_{avg} = \frac{1}{2}Re\left\{\iiint \mathbf{J} \times \mathbf{B}^{*} dV\right\}, \tag{5}$$

where $Re\{x\}$ denotes the real part of the complex number x and * denotes the complex conjugate. In practice, the above integral can be rather difficult to calculate directly, and so a first-order approximation is often preferable. It begins by calculating the magnetic moment **m**, defined as

$$\mathbf{m} = \frac{1}{2}\iiint \mathbf{r} \times \boldsymbol{J} dV. \tag{6}$$

If the magnetic field profile is approximately linear, we can then calculate $\mathbf{F}_{avg}$ using the much simpler expression (Jackson, 1999)

$$\mathbf{F}_{avg} = \frac{1}{2}Re\{\nabla(\mathbf{m}\cdot\mathbf{B}^{*})\}. \tag{7}$$

Using the above formulation, (Rony, 1964) was able to derive a closed-form approximation for net force acting on a sphere with uniform conductivity. Given some linear magnetic field profile with the form $\mathbf{B} = (B_0 + \alpha x)\hat{\mathbf{z}}$, it is assumed that the linear gradient α is a small perturbation relative to the uniform component expressed by B_0. The net force acting on the particle can then be shown to satisfy

$$\mathbf{F}_{avg} = -\frac{3\pi\alpha B_0 a^3}{\mu_0}\left[\frac{1}{3} - \frac{1}{q}\frac{\sinh(q) - \sin(q)}{\cosh(q) - \cos(q)}\right]\hat{\mathbf{x}}, \tag{8}$$

where $q = a\sqrt{2\omega\mu_0\sigma}$. Although this expression is only an approximation, the experimental work of Lohöfer (1989) and Ray et al. (2018) have both demonstrated that it provides considerable accuracy under many real-world conditions.

In Fig. 3, a plot of the force acting on various metal spheres with radius $a = 1.0$ cm when excited by a sinusoidal magnetic field intensity of $B_0 = 50$ mT at a field gradient of $\alpha = -1.0$ T/m, is shown. An important characteristic of the force profile is a saturation effect where the net force levels off as frequency is increased. This is primarily due to the skin effect, which tends to squish the current density into a thin film along the outer surface of the particle as frequency approaches infinity. For a highly conductive metal like copper ($\sigma = 58$ MS/m, Mega Siemens/meter), the force quickly saturates at less than 1.0 kHz in frequency. For less conductive metals such as brass ($\sigma = 16$ MS/m), the frequency needs to be much higher to achieve the same level of force.

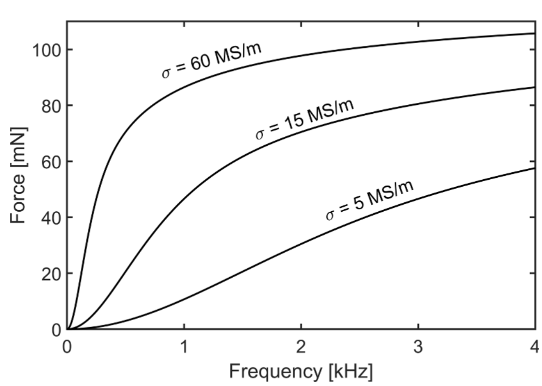

Fig. 3. A plot of the force acting on metal spheres with varying conductivity. The particles have a radius $a = 1.0$ cm when excited by a sinusoidal magnetic field intensity of $B_0 = 50$ mT at a field gradient of $\alpha = -1.0$ T/m.

Once the net force has been calculated, it becomes possible to predict the kinematic trajectory of a metal particle as it travels through the magnetic field profile. This is accomplished by simply discretizing Newton's laws of motion wherein the continuous-valued derivatives are replaced with finite-difference expressions in time. For example, the change in velocity **v** is calculated using

$$\Delta\mathbf{v} \approx \boldsymbol{a}\Delta t \tag{9}$$

where $\boldsymbol{a} = (\mathbf{F}_{avg})/m$, m is the particle mass, and Δt is some arbitrarily small increment in time. Similarly, the change in position vector **r** is likewise be calculate using

$$\Delta\mathbf{r} \approx \mathbf{v}\Delta t \tag{10}$$

If one so desires, it is also possible to account for the spin and orientation of the metal particle. This can often be a significant source of extra deflection if the particle must push against the flooring beneath it before rotating. We begin by calculating the net, time-averaged torque vector using

$$\tau_{avg} = \frac{1}{2}Re\left\{\iiint \mathbf{r} \times \left(\mathbf{J} \times \mathbf{B}^{*}\right)dV\right\}. \tag{11}$$

As we saw with the force calculations, it is often possible to treat the magnetic field profile as nearly uniform with only a slight linear gradient. In this scenario, the net torque simplifies greatly into

$$\tau_{avg} = \frac{1}{2}Re\{\mathbf{m} \times \mathbf{B}^{*}\}. \tag{12}$$

Once the torque has been calculated, it is then possible to apply a similar discretization to the angular velocity and angle orientation. This method has served as the basis for many well-known studies in eddy current separation, including (Nagel, 2018a; Rem et al., 1998,1997; Zhang et al., 1999c).

3. Current commercial offerings of eddy-current separators

Despite the variety of research and commercial ECSs, all of the current ECS companies offer minor variations of the conventional rotary-drum type of separator (i.e., mechanical movement of permanent magnets). This type of separator has established itself as the default in this industry. The design (Fig. 2) essentially consists of a belt conveyor with its drive at the feed end and a high-speed rotor with permanent magnets of alternating polarity at the discharge end. The magnetic rotor, positioned within a separately rotating non-metallic drum, revolves typically at ≈ 3000 rpm while the outer drum cover rotates at the belt conveyor speed. Nonconductive materials 'drop' at the end of the conveyor while non-ferrous metals are propelled forward, or 'thrown' over a splitter. Some manufacturers even provide an adjustable eccentricity for the rotor so as to optimize the deflection trajectory.

Quality metrics used to quantify a separation are recovery (R) and grade (G). To define these terms, consider two initial masses, m_0 and M_0, of differing materials mixed together before the separation. In an ECS, the collection bins consist of two bins, labeled bin 'A' and bin 'B'. The desired outcome is for all of the mass m_0 to collect in bin 'A' and all of mass M_0 to collect in bin 'B'. We can define M_A and M_B as the total masses from M_0 that fall in to their respective bins. Common industry terms for these bins are "throw" and "drop." Let bin 'A' represents the "drop" bin, or fluff/undesired material, and the "throw" bin is bin 'B', the desired nonferrous metals. The recovery (R) and grade (G) of bin 'A' and 'B' can be defined as:

$$R_A = \frac{m_A}{m_0} \tag{12}$$

$$R_B = \frac{M_B}{M_0} \tag{13}$$

$$G_A = \frac{m_A}{(m_A + M_A)} \tag{14}$$

$$G_B = \frac{m_B}{(m_B + M_B)} \tag{15}$$

Generally ECS are effective at recovering nonferrous metals out of nonmetallic fluff in most separations. Moreover, these systems have high throughput (t/h) and are generally reliable. There is a wide range of sizes and prices for the systems offered by ECS manufacturers. Some manufacturers sell complete systems while others provide parts to recyclers and/or equipment manufacturers who offer turnkey systems. Although robust, ECS rotary-drum type separators have inherent limitations.

An inability to throw awkward geometries (e.g., wires, thin foils/coupons) is one limitation. For example, copper wires do not throw well. Moreover, printed circuit boards contain an appreciable amount of nonferrous metals; however, they fail to throw properly due to their makeup. Also, heavy low-conductivity materials do no throw well. Generally, metal recycling plants use other methods to recover these types of materials, but is not the subject of this work (e.g., optical sorters and density separation).

In all of these ECSs, the magnetic flux density and frequency are determined by the design of the rotor; namely, by the number of poles and strength of the permanent magnets inside the drum and its rotational speed. Common ECS designs also struggle with small particles (< 1 mm), which require high excitation frequencies (kHz-MHz) before they will throw. To overcome this, manufacturers typically increase the number poles (e.g., 32 poles are common). However, there is a limit on this due to a reduced B-field. The more common designs use barium ferrite magnets, which work well to separate Al beverage cans from trash. For high tonnage applications with maximum recovery, separators use rotors with big blocks of strong long-life rare earth magnets to achieve over 5 kG (0.5 T) at the surface of the conveyor belt. The field depth determines how thick the scrap layer over the belt can be without deteriorating the separation efficiency.

4. Historical survey of eddy current separation technology

The first record of observing eddy currents, which was called "rotatory" magnetism, and the fact that most nonferrous conductive bodies could be magnetized, was reported by François Arago in 1824 (Baily, 1879). The phenomenon, by which electrical currents appear in any conductor when exposed to a time varying magnetic field, or rather, electromagnetic induction, was later further explained by Faraday in 1831 (Anderson, 1993). In 1834, Heinrich Lenz pronounced his law that the induced current in an object creates another magnetic field opposing the field that induced it. Léon Foucault is credited with having discovered eddy currents (also known as Foucault currents) in 1855 when he realized that the force required to keep rotating a copper disc became greater when it continuously passed between the poles of a magnet, the disc becoming heated by the eddy currents induced in the metal (principle behind energy meters in our houses). In arbitrarily shaped solids, there are no obvious circuit paths (as when we close a piece of wire) so that multiple tortuous circuits throughout the material (depending upon local spatial mass and conductivity distributions) are established, resembling the eddy currents observed in liquids.

The concept of the alternating magnetic field eddy-current separator was introduced by Edison (1889) and Maxim (1889) separately in 1889. These initial designs involved magnetic separators that used rotating electromagnets energized by DC currents. In the same year as Edison and Maxim, (Moffat, 1889) patented an electromagnetic separator that used a stationary electromagnet energized by AC currents.

In 1913, (Isbell, 1913) patented the use of electromagnets energized by poly-phase currents, generating a traveling magnetic field. This separator was apparently intended for the use in the concentration of magnetic particles; that is, it relied on magnetic attraction rather than eddy-current repulsion effects. In 1923 a patent by Mordey (1923) was granted for the use of traveling magnetic fields generated by poly-phase currents for the concentration of metal particles.

A concentrator exploiting the rolling action imparted to metal particles by a rotating magnetic field had earlier been patented by McCarthy (1922). Lee (1931) and Benson and Falconer (1969) further elaborated on the principle of repulsion of metal particles from regions of strong, high-frequency magnetic fields. Lovell (1946, 1951) was able to show that with a suitable combination of several coils energized by high-frequency currents, the repulsive force could be converted to an attractive force over a selected volume. Benowitz (1975) patent involved a magnetic pulley that attracted nonmagnetic metal pieces by a similar combination of high frequency coils.

In the 1970s, Vanderbilt University (Roos et al., 1976) contributed to some major developments of eddy-current separators. This group extensively tested an eddy-current separator utilizing phase current. The electromagnet used in this separator bore a strong resemblance to a three-phase motor, except that the motor had been opened up and laid flat. This type of electromagnet was, therefore, referred to as a 'linear motor'. Linear motors were powered by 60 Hz current, and installed both below and above the conveyer belt. Another type of separator that received considerable attention was the 'popper' or the 'pulsort.' Here, the particle stream was exposed to a sequence of strong, short magnetic field pulses, generated by discharging a condenser bank through a coil. All metal particles in front of the coil at the time of the pulse are lifted out of the stream. In addition, the work at Vanderbilt University extended to separators in which the particles are adopted to fall by gravity through a magnetic field having unbalanced field gradients (Vanderbilt, 1973b), and separators in which a traveling magnetic field was generated by rotation of DC electromagnets and permanent magnet assemblies (Vanderbilt, 1973a).

Schlömann (1975) described the use of permanent magnets for removal of nonmagnetic metals from solid waste. Permanent magnets were embedded in strips of alternating polarity at a 45° angle to the surface of a ramp axis. Deflection of the conducting particles was a function of the length and inclination of the ramp; the field strength of the magnets at the ramp surface; the conductivity, density, shape, size, and initial velocity of particles; and the coefficient of sliding friction between the particles and the ramp. The disadvantage was that the initial velocity of the particles was the only factor that altered the magnitude of the frequency for a given periodic array of permanent magnets.

Morey (1979) used a linear motor with a frequency range of 400–800 Hz to generate a traveling magnetic field wave. Separation was achieved for particles larger than 6 mm when passed through the traveling wave along the face of the linear motor.

Schloemann and Reiner reported on two types of inclined plane separators in 1979 (Schloemann and Reiner, 1979). The two separators were specifically designed for particles of 1–5 mm (shredded Al scrap and plastic) and used permanent magnets to induce eddy currents. One of the separators, the "channel separator" consisted of two inclined steel plates with an array of magnets (barium ferrite) on the two sides facing each other. The other separator examined was a "rotary disc separator" using samarium cobalt magnets attached to two discs, which are rotated at high speed. High grade and recovery (99%) were observed for feed rates of 9.5 kg/h (0.63 ton/h).

In 1979 (Trodahl, 1979) developed a nonlocal method to calculate eddy currents in ultrafine metallic particles (nm range). The approach leads to energy loss calculations smaller by a factor of 5/8 compared when using the usual Drude model. However, the model does not account for adsorption of far-infrared radiation, which was later accounted for in a follow up publication (Trodahl, 1982).

Zarkhova (1980) patented the use of two electromagnets with fields perpendicular to each other to align falling particles. The top electromagnet was used for pre-orientation of asymmetrical particles, and the bottom electromagnet produced the magnetic force. Electrically conductive particles entering the first air gap were orientated so that their maximum cross-sectional areas became arranged along the magnetic field lines of the second magnet. Electromagnetic forces acting on the particles greatly increased with this orientation, thus increasing the angle of deflection of the electrically conducting particles. However, this method was not verified by experiment, and the theoretical background is still inadequate.

Schloemann and Facinelli (1981) made an attempt to enlarge the unit capacity by making use of herringbone-like magnet patterns to increase the throughput. This separator was claimed to have a substantially higher capacity than conventional ramp separators of similar size. Ramp-type separators are generally sensitive to magnetic materials present in the feed, which block up the material flow and shield proximity of conducting particles to the magnets.

In the 1970s and 80s, the Raytheon Research Division, USA, made developments in the area of permanent magnetic field separators. Two types of system were investigated: an inclined table or ramp separator which consisted of an array of permanent magnets with alternating polarities mounted under an aluminum or stainless steel sheet; and a rotary drum separator that can be simply envisaged as a ramp separator rolled into a drum formation (Kercher and Webb, 1982). Unfortunately, this did not prove to be commercially viable, as it was susceptible to particle shape variation, friction of the ramp surface, and limited throughput (Zhang et al., 1998a).

In 1988, the vertical eddy current separator (VECS) was introduced by Van der Valk et al. (1988), from Delft University of Technology, Netherlands. The VECS consisted of two vertical, parallel, mild-steel walls with magnetic strips of alternating polarities. The conducting particles passing through an inhomogeneous magnetic field were deflected, whereas the nonmagnetic particles fell under the action of gravity. This separator was basically a combination of two ramp-type separators standing vertically. Electrically conductive particles had to be sufficiently separated from nonconductive materials. This separator was thus not practical, due to the narrow separation channel. Deflecting forces in the static ECS are not strong enough for the recovery of small nonferrous metal particles, as the magnetic field is stationary. As these separators consume no power and have a simple layout, they are easy to operate, with little maintenance.

A paper by Van der Valk et al. (1988) in 1988 discussed several devices for eddy-current separators with magnetic fields generated by magnets. In static separators, the particles move through an alternating magnetic field generated by a configuration of permanent magnets on stable ramps, whereas in a dynamic field separator, the magnetic segments are mounted on the inside of two identical, vertical, parallel rotating disks. This configuration is used to generate a periodic variable magnetic field with alternating polarity. Both the motion of the permanent magnets and the motion of the particles cause the time dependent change of magnetic field acting on the particle. The repulsive forces exerted on block-shaped particles passing through the long magnet strips with alternating polarities were calculated by means of a theoretical model that is an extension of the Schloemann model. A quality factor describes the contribution of the configuration of the magnet strips to the repulsive forces, thus assisting in development of separators with minimum use of expensive magnetic materials. Similar to Schloemann's device, Han's device also requires a number of mechanical linkages to generate desired frequencies.

A study published in 1991 by Fletcher et al. (1991) examined the use of a stationary magnet on an inclined plane to separate a mixture of non-ferrous elements consisting of washers, coins, scrap laminae of Al, Cu, brass, and various insulators of arbitrary shape and dimensions (3–57 mm) was fed to the field boundary (100 × 50 mm electromagnet with a field of 0.9 T) at an angle of 45°. Without application of field, all the elements entered the tails collector (non-conducting bin). With the application of field, all the aluminum elements entered the cons bins (conductors). A few small elements entered the tails resulting in an average recovery of cons of 1.61%. To explain the experimental results, two-dimensional models were developed to predict the motions of two model elements, circular and rectangular. For a single boundary system, solution of the equations of motion was found to model the trajectories of model elements through the device.

Reid (1991) developed experimental phase-plane diagrams for different shapes of aluminum. No theoretical background supported these experimental results, however. The maximum frequency used was 450 Hz and was found to be useful for separation of irregularly-shaped large particles between 10 and 20 mm. Due to the complexity of construction and operating cost, eddy current separators with permanent magnets have replaced these category separators. Following the development of better materials for permanent magnets, nonferrous metal separation systems with low energy consumption and low operating cost have been developed.

Julius (1991) and Roos (1992) have different patents based on using mechanical moving magnets. Permanent magnets are used to achieve a changing magnetic field for creation of eddy currents in conductive materials. The disadvantage is the high frequency or fast rotor speed that is required to produce the needed magnetic force for finer particles.

Lee (1995) described the use of a solenoid for creating an electromagnetic field for separation. The separation apparatus consisted of a solenoid coil connected to a high-frequency AC source. When a source of free-falling particles was fed close to the coil end, the alternating magnetic field of the coil induced eddy currents in the electrically conducting particles. Interaction of the alternating, non-uniform magnetic field of the coil with the eddy currents in the particles produces electromagnetic forces on the electrically conducting particles in the direction of decreasing field intensity of the coils' magnetic field. Force interaction between the eddy-currents and the non-uniform magnetic field of the coil resulted in deflection of the electrically conductive particles. The drawback was that the separation was affected at regions of low magnetic field intensity; increasing the magnetic field intensity by increasing the current raised the power consumption and caused excessive heating, thus the method was found impractical.

In 1997, (Woltereck et al., 1997) examined the separation of aluminum cans through multiple strategies involving analytical, numerical, and experimental techniques. A two-dimensional parametric finite model was developed and compared with experimental measurements. The experimental measurements were conducted using an air coil of 170 windings. The DC resistance and inductance were measured to be 20 Ohm and 6.65 mH, respectively. In a typical experiment, a can was placed over the middle of the coil and tape was used to prevent the can from rolling sideways. The frequency was increased until the can achieved "lift-off." Comparing the simulated forces to the measured results provided acceptable agreement.

Rotating-disc eddy-current separators were initially developed by the Delft University of Technology group in the late 1980s (Zhang et al., 1998a). This device consisted of permanent magnets mounted on rotating mild-steel discs and exerts stronger forces than the VECS. The conducting particles are deflected radially due to the rotation of the magnetic field. Increasing the rotational speed of the rotating disc can increase the frequency of the acting magnetic field, and thus the deflecting force can be increased. Due to its low throughput, the rotating-disc separator is not commercially viable even today. Development of the rotating-disc separator led to belted-drum (BDECS) and rotating-drum (RDECS) separators (Zhang et al., 1998a). These designs incorporate high-energy permanent magnets, high-speed rotation, and optimization of the magnetic roll system to minimize the cost of equipment.

Saveliev's patent in 1998 (Saviliev, 1998) discusses the use of high-frequency AC to induce an alternating magnetic field in a coil-wound torroidial ferrite core. The AC frequency is set according to the specific resistivity of the targeted material. To account for particle size reduction, this method relies on increasing the AC frequency by non-mechanical means. This was a new proposed design consisted of a ferromagnetic core formed in a torroidial-like shape with an air gap. A coil is wound around the core and an alternating current is applied to the coil to induce an alternating magnetic field at the gap. By adjusting or setting the frequency of the alternating magnetic field, conducting particles of interest are imparted a trajectory which is different than the trajectory of particles not of interest. Despite the advantages of such a design by reducing mechanically moving parts and increasing the excitation frequency, it has remained unmodified until recently.

Rem et al. published a series of papers in 1997–1998 (Rem et al., 1998,1997) that developed mathematical models to simulate of the throw of particle on a drum eddy current separator for Al and Cu particles 3–30 mm in size. From their models, qualitative conclusions were drawn regarding the effects of particle size, shape, and conductivity on the particle trajectory. Their models developed also include the mechanical interaction between the particles and the transportation belt, as well as aerodynamic forces. The resulting particle trajectories were compared to experimental data both on the basis of full trajectories and statistically, in terms of the calculated and measured throw. The simulation software, ANSYS was utilized to numerically estimate the field of the drum and particle trajectories integrated with the software DASSL.

In a series of papers from 1998 to 1999, Zhang et al. (1998b, 1999a) examined the recovery of aluminum from electronic scrap using a newly developed High-Force® eddy current separator. Recovery of > 7 mm particles were in excess of 90% with a grade of 85% achieved at a feed rate of 0.3 kg/min (~0.02 t/h). The mechanism of separation was also discussed (Zhang et al., 1999a). Using similar materials as described in the previous studies, they also found that by rotating the drum counter to the direction of the feed belt results in competition between the tangential eddy current force and the dynamic frictional force created by the electromagnetic torque (Zhang et al., 1999b). It was found that the critical particle size for which the magnetic drum rotates backwards is about 4.8 mm. In this series of studies the particle trajectories of two-drum ECS was modeled and compared with experimental data (Zhang et al., 1999c).

In 2001, (Lungu and Schlett, 2001) proposed a new design of ECS, or the so-called vertical drum eddy-current separator. This design consists of a vertical spinning drum covered with permanent magnets with alternating poles. The particles are fed into the field on an oblique trajectory. The results of grade and recovery for particle mixtures consisting of the following were demonstrated: (A) irregular shaped PVC (2–6 mm) + Cu wire (4 mm diameter) in 50/50 wt% mixture, (B) Cu wire with 1–2 mm diameter and lengths of 2–6 mm + Pb particles of irregular shape, 2–6 mm in size, mixed 60/40 wt% Cu/Pb, (C) Cu wire 2 mm in diameter and 6–8 mm in length + Al particles of irregular shape, 2–8 mm in size in 20/80 wt% Cu/Al mixture. Comparative to these results, the values of grade and recovery obtained for the same types of wastes using a horizontal drum eddy-current separator, designed to separate millimeter-sized particles, are given. The claimed advantages of the vertical design lie in fact that the efficiency is close to the one of the horizontal design, and the cost of the equipment is lower. However, the disadvantages are that the intermediate product must be passed again through a separation process. For example, in the case of mixtures B and C, the intermediate product collected in the drop bin had a mixture composition close to that of the feed material.

Another new design was proposed by Meier-Staude et al. (2002) in 2002. This design consists of placing the rotating magnetic drum above the feed belt at the end of the feed belt rather than below. Thereby the rotation of the conductive particles contributes positively, increasing the total translational acceleration and enhancing effective separation. The mixture of material used for separation demonstration in this study consisted of Al and Cu wires with 0.5–4 mm diameter and 3–12 mm length. One kilogram of this mixture was sieved were 361 g of 1.6–2.5 mm particles were recovered and used for the separation experiments. Recoveries of 72–97% and grades of 61–67% were observed under optimal conditions.

Schlett et al. (2002) proposed a static design. This design consists of a stationary magnet consisting of a flat rectangular coil on an inclined plane. Particles are then fed down the sides of the stationary magnet and any excited particles are deflected away from the wall. The more insulating particles are collected at the bottom of the inclined plane. Recovery and grades greater than 90% were observed for two types of mixtures, (i) Cu particles 2–3 mm in diameter, and (ii) Fe particles of 1 mm size mixed with plastic particles of the same sizes.

In the same year, (Schlett and Lungu, 2002) proposed a design consisting of a rotating magnetic disk parallel to an inclined plane. Recoveries of 79–97% and grades of 78–93% were realized using particles between 2 and 4 mm in size and consisting of Cu-Pb mixtures of different ratios. The amount of feed material processed per experimental run was approximately 100 g.

Also in 2002, Lungu and Rem (2002) proposed another design of separators. In this study, an inclined rotating drum was proposed. The particles to be separated are fed into the field on an oblique trajectory, hitting the drum, and are deflected in the variable field under electrodynamic and mechanical interactions. Two types of particle mixtures were examined. These consisted of: (i) Cu–Pb mixture containing Cu wires with diameters between 1 and 2 mm and lengths between 2 and 6 mm, and Pb particles of irregular shapes and dimensions between 2 and 6 mm. The proportions were 60% Cu to 40% Pb and, (ii) Cu–Al mixture containing Cu wires (diameter 2 mm, lengths 6–8 mm) and Al particles of irregular shapes and dimensions between 2 and 8 mm. Recovery and grades as high as 80–90% were demonstrated.

A new design where the particles are separated in liquid medium (room temperature water) using a rotary drum was examined by Kohnlechner et al. (2002). The time during which the particles are in the presence of the variable magnetic field depends on the characteristics of the device, but it is usually short. When the particles move in the liquid in the presence of the magnetic field, the time can be increased, having a favorable effect upon the separation process, even in the case of small particles (< 5 mm). At the same time the magnus effect, which has a positive contribution to the separation process, operates upon the particles, which are in a rotation movement. Particles of Al and Cu wires having 0.5–3 mm cross-section and 3–10 mm length were used. The grade input for Al and Cu were 0.57 and 0.43, respectively. Under the operating conditions examined, grade recovery curves were generated. Grades and recoveries in the rage of 90–95% for Al and 85–90% for Cu were observed.

In 2004, a study by Maraspin et al. (2004) modeled the throw, or trajectories, of 10–36 mm sized particles of magnesium and aluminum cast alloys in a conventional rotary belt feed ECS. The study showed that the primary particle parameters are size, conductivity, and initial orientation. The effects of particle–particle interaction on the grade and recovery was predicted by considering two different types of collisions between nonferrous and nonmetal particles. The trajectories of individual particles were estimated numerically by approximating their shape in terms of cylinders, spheres, and disks. Their estimations were accurate to about 10% at low feed rates.

Also in 2004, Settimo et al. (2004) examined the effect of a slightly wet feed (10–15%) using a classical rotary belt feed ECS. With a wet feed, smaller particles become stuck to the belt as the adhesive force is of the same order of magnitude as gravity forces. The action of the magnetic rotor makes the non-ferrous particle tumble and break loose from the belt. Granular waste streams consisting of 2–6 mm particles were examined. The waste streams were made of stone and glass with ~3% non-ferrous metals (aluminum, copper, zinc, brass, and lead). The separation demonstrated good recovery for aluminum (> 95%) at feed rates of 4 t/h per meter width of separator.

Lungu (2005) presented a new approach to rotary drum ECS. In this design, the rotary drum below the feed belt was angled oblique to the feed belt. The axis of the drum and the direction of displacement of the belt make a certain angle, depending on the physical properties of the particles subjected to the separation process. Particle mixtures of Cu/Pb (64%/36%) and Cu/Al (40%/60%) mixtures, 2–5 mm in size with irregular shapes were used. Grades and recoveries for Cu were both ~95% and 96–97% for Al at an oblique angle of 45 degrees to the belt. Using the same particle mixtures, Lungu (2009) examined the separation efficiency of a single drum designed with two successive separation steps. Marginal grains in grade and recovery were observed for one versus two-step separation. However, the advantage of the two-step separation is realized in the separation efficiency, which was defined as the difference between recovery and product impurity (Fourie, 2007; Kawatra and Eisele, 2001).

Ruan and Xu (2011, 2012) examined the use of a rotary drum ECS for recovering Al flakes from waste toner cartridges. In these works, they identified particular operating parameters for this type of sort. A new model of repulsive forces was proposed, (Ruan and Xu, 2011) taking into account such as area per magnet facing the particle and the maximal cross sectional area of the horizontal flakes. More recently, (Ruan et al., 2017) examined the application of recovering Al from e-waste (i.e., crushed refrigerator) using a rotary drum ECS. These studies reported the effective separation in terms of separation distance, or throw, of the particles as a function of operating parameters. Data on the recovery and grade of sorted material is not reported directly.

In 2015 Hu and Bakker (2015) compared wet (i.e. alkali leach) and dry (i.e. ECS) methods to recover aluminum from Amsterdam municipal solid waste incinerator bottom ash. Their study found that a combination of wet and dry processes was the best to recover aluminum residues in the −20 mm fractions compared to a single wet or single dry process. Also in 2015, (Yao et al., 2015) reported on the design of an ECS using a high gradient superconducting magnet (NiTi/Cu) with 5 T field strength and 36 T/m gradient. The main components of this system include superconducting coils, high temperature superconductor leads, cooling system, cryostat, and an iron shield. The paper describes a detailed development of the system; however, a demonstration of a sort was not reported.

Amir et al. (2016) reported on the technical and economic development of a low-cost ECS for household waste treatment. Numerical simulation of aluminum beverage cans trajectory was carried out for a rotary-drum ECS. The economic analysis revealed the design to be practical for use in Africa.

Zheng et al. (2016) examined the recovery of Al particle from waste toner cartridges using eddy current separation (belted drum). It was found in their study that hollow aluminum particles existed in crushed waste toner cartridges, and these particles exhibited a reduction in throw when compared to solid aluminum particles of the same size. To improve the efficiency of separating hallow aluminum particles, models of eddy current force and movement behaviors of hollow aluminum particles in eddy current separation were developed. Aluminum particles were collected from crushed waste toner cartridges with a variety of shapes both solid and hollow. The size of the particle raged from 15 to 40 mm.

Ruan et al. (2016) demonstrated a process to recover metal and oil from waste capacitors on printed circuit boards. First, crushing liberated the materials. Second, the ferrous (nickel alloy) and nonferrous (aluminum) were separated by magnetic and ECS methods. Nonmetallic components were then transformed to oil to vacuum pyrolysis. Their study showed that under optimized conditions, crushing these waste capacitors down to 5 mm, 98.9–100% recovery of the nonferrous fraction could be recovered.

Li et al. (2017) demonstrated the application of ECS for separating printed circuit board materials from plastic generated from crushed cell phones. Numerical simulation was applied to determine the trajectories of plastic, printed circuit boards, and pure metal particles. Two size ranges were examined, 2.5–5 mm and > 5 mm particles of screened hammer milled cell phone material. Design of experiments was utilized to arrive at the optimum separation conditions, where ~95.5% of printed circuit board material can be recovered for > 5 mm particles.

From about the late 1990s to present, Rajamani and coworkers (Dholu et al., 2016; Kim, 1998; Nagel, 2018b; Naidu, 2010; Rajamani et al., 2016; Ray et al., 2018; Saurabh, 2009; Saurabh and Rajamani, 2012; Smith et al., 2017) at the University of Utah have designed and developed an eddy current separator system which overcomes some of the limitations of belted-drum type eddy current separators. Electrodynamic Sorting (EDX™), or variable-frequency eddy current sorting, is an evolution of sorting technology primarily focused at nonferrous metal separation and small particle separation (< 1″ or 25.4 mm) (Rajamani et al., 2016).

Advantages of the EDX™ system include minimal mechanically moving parts, a system that can operate at higher excitation frequencies

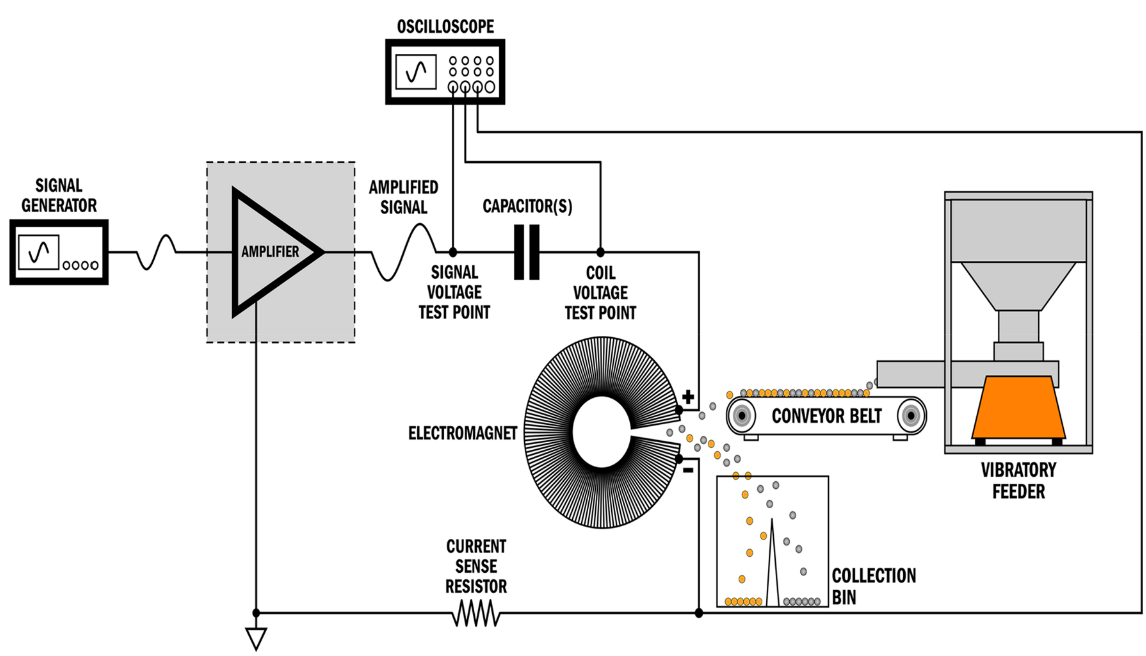

Fig. 4. Schematic of electrodynamic sorting system (EDX™), or variable-frequency eddy current sorting system. The non-conducting particles are orange (left collection bin) while the conducting particles are grey (right collection bin). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Table 2
Summary of typical variables of separation and optimization.

Variable of separation	Variables for optimization
Particle size	Feed rate
Particle shape	Feed method
Particle conductivity	Excitation frequency
Particle density	Splitter settings
Particle size distribution	
Moisture content	
Metallic content	

(up to 50 kHz), and low energy demand (Fig. 4). Being able to operate at higher excitation frequency enables the separation of smaller particles (e.g., $\leq\sim 5$ mm). The principle of this design was originally pioneered by Moffat (1889), and later developed more by Saviliev (1998); however, the design has remained relatively unrefined. With a new design, (Dholu et al., 2016) demonstrated the sorting of 6.0 mm sphere mixtures of Al/Cu, Cu/Brass, and Al/Brass with nearly perfect recovery and grade. The same configuration also demonstrated promising sorting of Al alloys from a mixture of Al alloys. For example, the separation of Al-110/Al-2024, Al-110/Al-6061, and Al6061/Al-2024 series alloy mixtures using 12 mm size spheres, recoveries and grades of 85–95% can be realized. Another major advantage of the EDX^{TM} system is the ability to easily adjust the excitation frequency. This enables the system to be "tuned" for a specific metal or alloy.

With a similar configuration, (Smith et al., 2017) demonstrated the application of sorting end-of-life photovoltaic materials (i.e., Al, Si, and CdTe 1–3 mm granules). Recovery and grades of 85% and greater were achieved operating at an excitation frequency of 21.4 kHz and an average throughput of approximately 9 kg/h (0.009 t/h).

5. Future challenges and direction

Having reviewed the different types of eddy-current separators (ECS) described in the scientific and technical literature for the last 130 some years, in this section we aim to discuss future challenges and potential directions for development in ECS research. The design and performance of the rotating belted-drum type eddy current separators have been improved substantially in the last ten years, primarily due to advances in magnet materials and magnet configurations, as well as a better understanding of the separation mechanisms (Rem et al., 1998, 1997; Zhang et al., 1999b,c). Yet, problems associated with separation of small particles ($\leq\sim 5$ mm), remains an arduous challenge to date.

Because most recycling streams are roughly sized, randomly shaped, and have variable material composition, laboratory testing is needed for the manufacturer to determine the best-suited machine and range of settings for a given separation. Factors that influence separation and parameters that manufacturers normally optimize are outlined in Table 2.

Current eddy current separators are primarily used to separate metallic aluminum components from recycle streams. An area in where ECS has gained considerable use is in automotive shredder residue (ASR) aluminum recovery (Jirang and Roven, 2010; Morselli et al., 2010). The development of eddy-current separators capable to separate smaller particles with a tunable frequency (e.g. EDX™ system), widens the application to environmentally recover and recycle other non-ferrous metals other than predominantly Al. Potential applications of ECS in the recycling of:

- Alxxx series alloys (Dholu et al., 2016);
- Zorba and Twitch (Al, Cu, Ni, Brass and Al automobile scrap) (Rajamani et al., 2016);
- Photovoltaic materials (Smith et al., 2017);
- Lithium-ion battery materials (Li/Co/Ni/Mn oxides, Cu, Al);
- Recovery of rare earth elements;

may be possible. Separation based on materials that have relatively large differences in conductivity appears to be easily achievable with this technique. On the other hand, separation of materials with relatively close conductivities presents a challenge. Moreover, it is not just also the differences in conductivity, but the absolute magnitude of the conductivity. A higher excitation frequency of the magnet will be required to achieve effective separation of less conducting particles.

Despite the advancements made in ECS designs and developed models, there still remain some basic and applied questions in ECS that have yet to be resolved. For example, how much influence does humidity or dust/coating on metallic particle influence induced eddy currents (Ruan and Xu, 2016)? How much influence does temperature have on induced eddy current strength? Given the current state of technologies, what is the lower limit of particles that can effectively be separated from a stream? How can the effective throughput be increased? How to mange composite materials? These are examples of a few questions that still remain active areas of investigation and may lead to improvements in ECS design and applications.

6. Conclusion

In this review we have made an attempt to summarize the current available literature on eddy current separators for recovery of non-ferrous metals from waste streams. Many technological breakthroughs have enabled the industrial scale use of such systems in metal scrap sorting and recycling scenarios. However, there still remains knowledge gaps in the fundamental understanding the of separation mechanism. Moreover, the ability to model such systems remains a technical challenge with substantial room for improvement. Current limitations in design (i.e., rotary belt drum ECS) limit the broader applications of this technology, and its full potential has yet to be fully realized. Future developments of this technology will potentially have large impacts on the metal scrap and recycling industries.

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