Physical Separation in Science and Engineering, 2004,
Vol. 13, No. 1, pp. 15–23

EDDY CURRENT SEPARATION OF FINE NON-FERROUS PARTICLES FROM BULK STREAMS

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(Received 13 March 2004; In final form 13 April 2004)

Recovery of fine non-ferrous metals from waste streams is a notoriously difficult problem in eddy current separation technology. Existing processes either have a low capacity or an incomplete recovery for particle sizes below 5 mm. In a new process, the particles are fed slightly wet to make them stick to the surface of the conveyor belt. The action of the magnet rotor makes the non-ferrous particles tumble, so that they break loose from the belt and end up in front of the rotor. The new process combines a relatively high capacity with an almost complete recovery, even for heavy and poorly conducting non-ferrous metals.

Keywords: Non-ferrous metals; Wet separation; Eddy current; Small particles

1. INTRODUCTION

Traditional eddy current separators have a problem in recovering non-ferrous particles with a diameter of less than 5 mm [1,2]. Such machines rely on the eddy current force of the magnet rotor on the non-ferrous particles to create a separation. Unfortunately, this force scales as the fifth power of the particle size for small particles [3], whereas the mass of a particle scales only with the third power. The result is that frictional forces dominate the separation for small particles. One way to solve this problem is to build specialized rotors with many small poles, to increase the frequency and the gradient of the field at the position of the particles. Experiments with these rotors by Fuhrmann show that aluminium particles down to 1 mm in diameter can be recovered, but at a relatively low throughput of about 1 t/h per metre width of the rotor [4].

A more fundamental solution in dealing with fine materials is to use the torque of the magnet rotor on the metal particles in the feed to introduce a selective separation effect. The torque deriving from eddy currents also scales as the fifth power of the particle size, but so does the particle moment of inertia. Therefore, non-ferrous particles of all sizes

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ISSN 1478-6478 print: ISSN 1478-6486 online
DOI: 10.1080/00207390410001710726

acquire angular velocities of the order of a 1000 rad/s in air within a few tens of milliseconds after entering the field of the rotor. Several mechanisms have been tried to convert the spinning of the non-ferrous particles into a separation effect. An interesting possibility is to use the Magnus effect, i.e. the force acting perpendicularly to the trajectory of a rotating body that is falling in a fluid. Since this force derives from the fluid around the particles, it is not necessary to feed in a monolayer (see [5] for an analysis of the need of monolayer feeding in traditional eddy current separation) and so the throughput can be as high as 6 t/h per metre of rotor width. The separation works both in air and in water [6,7]. A disadvantage of the Magnus separator is the limited recovery, which is typically about 70–80% for aluminium and less for heavy or poorly conductive metals.

Alternative mechanisms on the basis of the torque use the collisions of rotating particles with a surface shielding a fast-rotating magnet [8]. Lungu invented a machine in which the feed mixture is transported over an inclined surface covering a fast-spinning magnet disk. The non-ferrous particles start to jump and those particles that reach a certain height above the surface are collected. This latter mechanism can also be shown to separate different types of non-ferrous metals from each other [9]. Lungu's device generally has a high recovery but its capacity is limited.

The most straightforward separation mechanism on the basis of the torque is to make the particles roll or jump forward on a surface [10]. Experiments by Zhang *et al.* on a traditional eddy current separator show that this mechanism works well for non-ferrous particles with a granular shape, if all the particles are small enough to avoid domination of the linear eddy current force [2]. This force is normally counteracting the effect of rolling, except when the rotor is above the conveyor belt, as in the design by Meier-Staude *et al.* [11]. A major problem of separation by rolling is that the non-ferrous particles have to be able to develop a significant differential speed with respect to the rest of the feed on the conveyor belt without being stopped by collisions with other particles. In practice, this means that the surface of the belt cannot be covered efficiently, and so the capacity of this process is again relatively low.

Recently, one of the authors developed a new mechanism for the recovery of small non-ferrous particles based on the eddy current torque [12]. The separation uses the torque to break the adhesive forces that make wet particles stick to the conveyor belt. Since the torque of the magnet rotor applies selectively to metal particles, only these are liberated from the belt and are collected in front of the rotor. Non-metal particles remain stuck to the belt and are released below the conveyor (see Fig. 1). The new process has a relatively high capacity because the non-ferrous particles do not need to accelerate in order to be separated and so the surface of the conveyor belt can be covered efficiently. Since the force necessary to break the adhesive forces is small, poorly conductive and heavy non-ferrous particles are also recovered. Finally, the process can be run on a conventional eddy current separator. Below, we will give the theoretical background of the separation mechanism and report the results of experiments on an actual waste stream.

2. THEORY

In a traditional eddy current process, the feed is separated into a non-ferrous concentrate, a non-magnetic and a magnetic fraction. As the mixture approaches the

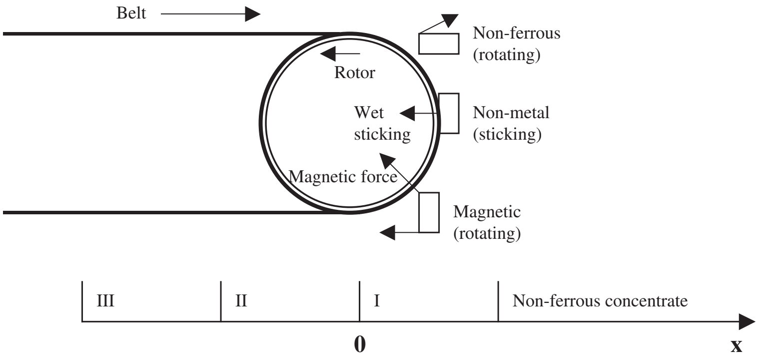

FIGURE 1 Wet magnetic separation with a counter-rotating magnet rotor. Non-metals end up in compartments I, II and III, magnetic materials in compartments I and II.

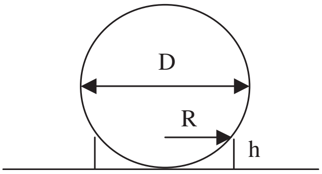

FIGURE 2 Geometry of wet bond.

rotor, the non-ferrous metals are accelerated by the magnetic field in a forward and upward direction and end up in the compartment far from the rotor. Of the remaining material, the non-magnetic particles leave the belt at, or slightly beyond the point where the belt curves downward. Since all of these particles have the same initial speed, i.e. the belt speed, they follow more or less the same trajectory into the compartment close to the rotor. The magnetic particles are attracted by the magnet rotor and therefore stick to the belt surface until they are released at a point under the conveyor, where the magnetic field is too weak to oppose gravity.

The effect of adding water to the feed is to glue all the particles to the belt surface. For small particles, this adhesive force is of the same order of magnitude as gravity. Without the action of the rotor, therefore, virtually all particles would stick to the belt and end up in the 'magnetic fraction'. However, the rotating magnetic field makes both the non-ferrous particles and the magnetic particles spin, with the effect that the water bonds between these particles and the belt are broken. If the magnetic attraction on the magnetic particles is sufficiently large, these will remain on the surface of the belt, but the non-ferrous particles will be liberated at some point and follow more or less the path of the non-magnetic materials in a traditional eddy current process.

In order to quantify the adhesive force, consider a spherical particle of diameter D that is connected to a surface by a cylindrical mass of water of some volume V (see Fig. 2). The energy contained in the air–water interface is about:

$$\Phi = 2\pi R h \gamma \approx 2\gamma\sqrt{\pi V h} \tag{1}$$

R and h are the radius and height of the cylinder, and $\gamma \approx 73 \times 10^{-3}\,\mathrm{J/m^2}$ is the surface tension for water and air. The force gluing the particle to the surface, as a result of the interfacial energy, is:

$$F = d\Phi/dh\big|_V = \pi R\gamma \tag{2}$$

The total adhesive force is even larger, as it also includes the forces as a result of the solid–water interfacial energies involved in the water–particle and water–belt contacts.

Geometrical analysis shows that, if the sphere and the surface of the belt are coated with a water layer of thickness δ prior to feeding, a bridge of radius $R \approx 2\sqrt{D\delta}$ will form on feeding the sphere onto the conveyor belt, giving rise to an adhesive force of at least:

$$F = 2\pi\gamma\sqrt{D\delta} \tag{3}$$

For example, if $D = 3\,\mathrm{mm}$ and $\delta = 0.2\,\mathrm{mm}$, the force F equals $0.4 \times 10^{-3}\,N$, which is about the same as the gravity force on a stone particle of the same size. For non-spherical particles, the force may be higher (relative to their mass), because such particles rest on the belt with the part of their surface that has the largest radius of curvature. On the other hand, strongly curved pieces, such as large pieces of wire have little contact with the belt in relation to their total volume.

Although the adhesive force is strong enough to keep most of the non-metal particles glued to the belt surface during the first half of the belt turn, the eddy current torque can easily provide the force that is needed to break the bond for the non-ferrous particles. For these particles, the torque is

$$T = smB^2(\sigma/\rho)\omega D^2 \tag{4}$$

where B (Tesla) and ω (rad/s) are the magnetic induction and the rotational frequency of the field of the rotor, m is the mass of the non-ferrous particle (kg), (σ/ρ) ($\mathrm{m^2/Ohm\,kg}$) is the ratio of the electrical conductivity and the density of the non-ferrous metal (see Table I) and s is a coefficient that depends on the particle shape and orientation (see Table II [13]). The non-ferrous metal particle is able to break loose if the torque is of the order $FD/2$. For a typical water layer, e.g. $\delta = 0.2\,\mathrm{mm}$, and standard values of the field ($B = 0.3\,\mathrm{Tesla}$, $\omega = 3000\,\mathrm{rad/s}$), this criterion is met for well-conducting metals if $D > 1\,\mathrm{mm}$, whereas for metals like solder and lead it is realized for $D > 2\,\mathrm{mm}$.

TABLE I Density and electrical conductivity of metals and alloys

Metal	*Density* ρ (kg/m^3)	*Conductivity* σ (1/Ohm m)
Copper	8900	59×10^6
Aluminium	2700	36×10^6
Lead	11 400	5×10^6
Solder 50–50	8900	7×10^6

TABLE II Shape factor s defining the eddy current torque for particles of several shapes and parallel (||) or perpendicular (⊥) orientations of their axis of symmetry with respect to the axis of the rotor

Shape	*s*
Spherical	$\frac{1}{40}$
Cylindrical ‖	$\frac{1}{16}$
Cylindrical ⊥	$\frac{3}{64}$
Disk-shaped	$\frac{1}{64}$

3. EXPERIMENTAL RESULTS

In order to test the practical use of the separation concept, a number of experiments were conducted on a granular waste stream with a particle size between 2 and 6 mm. The waste contained mainly stone and glass with about 3% of non-ferrous metals, in particular aluminium, copper, zinc, brass and lead, as well as weakly magnetic and ferritic steel particles. All tests were run at a fixed belt speed of 1 m/s on a Bakker Magnetics eddy current separator with a counter-rotating rotor with 18 poles and a magnetic induction of 0.32 Tesla at the surface of the belt. Figure 3 is a schematic drawing of the equipment utilized.

The first two tests were run on a small sample of about 20 kg in which some of the non-ferrous metal particles were colored to serve as tracers. The initial test pointed out that at relatively low rotor speed the weakly magnetic particles are retained on the belt while the non-ferrous is liberated from the belt. In this test, two splitters were used to divide the feed into three products. Table III shows that the amount of non-ferrous tracer particles liberated from the belt is similar for rotor speeds of 1000 rpm ($\omega = 942$ rad/s) and 2000 rpm. At 1000 rpm, however, the weakly magnetic material remains on the conveyor belt, while some magnetic material is liberated at 2000 rpm. Therefore, it was decided to run the rotor at 1000 rpm, in order to avoid magnetic contaminants in the non-ferrous product.

The second test was used to define the best position of splitter 1. Figure 4 shows the recovery of the aluminum and heavy non-ferrous tracers versus the recovery of the remaining material as a function of the splitter position, at a level 65 cm below the axis of the rotor. On the basis of this graph, the splitter position for the final test was set to 30 cm horizontally away from and 65 cm below the axis of the rotor, to ensure maximum metal recovery.

A final test was done on a ton of the same waste at a feed rate of 4 t/h per metre width of the conveyor belt, to check for slow changes of the separation performance, e.g. due to fouling of the conveyor belt, and to correct for start-up effects in the small-scale tests. None of these factors were found to be critical, although it helps to clean the surface of the belt before the feeding point. The non-ferrous concentrate and the tailings were analysed by feeding samples of these fractions to a metal detector and separating the metal fraction in a heavy liquid at 3000 kg/m^3 into an aluminium fraction and heavy non-ferrous. A smelt of the heavy non-ferrous fraction was analysed by XRF to find the concentrations of the various metals. These figures were used to compute the recovery for all the metals in the product. Table IV shows that the recovery of heavy non-ferrous is complete. It is also clear that some aluminium was lost, possibly because

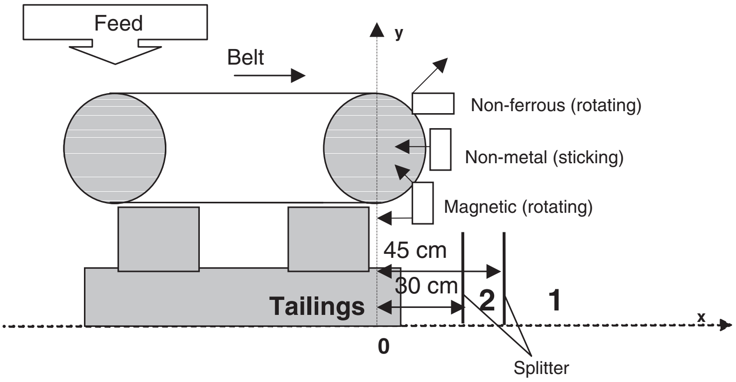

FIGURE 3 Collection of products and tailing with the ECS.

TABLE III Results at rotor speeds of 1000 rpm and 2000 rpm

	Al (g)	*Zn/Cu* (g)	*Mag* (g)	*Non-mag* (g)	*Total* (g)
2000 rpm					
Product 1	18.1	18.0	58.3	277.9	372.3
Product 2	17.5	21.4	476.5	6448.0	6963.4
Tailings	0.1	0.7	8036.0	4306.0	12 342.8
Total	35.7	40.1	8570.8	11 031.9	19 678.5
1000 rpm					
Product 1	21.4	17.4	–	311.4	350.2
Product 2	15.0	25.6	–	7671.4	7712.0
Tailings	0.5	–	5798.0	5349.9	11 148.4
Total	36.9	43.0	5798.0	13 332.7	19 210.6

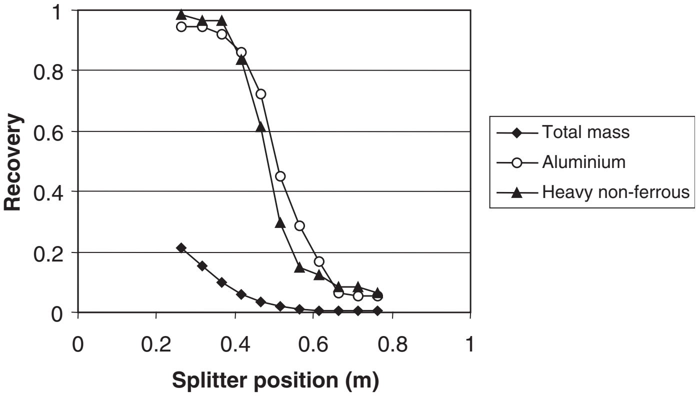

FIGURE 4 Recovery of metals and total mass in the product as a function of splitter position (horizontal distance from the rotor centre).

some of the aluminium particles were too heavily corroded for separation yet contained a sufficiently large metal core to trigger the metal detector.

A second experiment was conducted on the −4 mm fraction of shredded electronics scrap. As a first step, the material was screened on a 1 mm slit screen to remove most of

TABLE IV Separation results at full scale

	Feed		*Product 1 + 2*		*Tailings*	
	kg	%	kg	%	kg	%
Stone and glass	640.45	67.26	91.03	78.29	549.42	65.72
Weakly magnetic	231.91	24.36	–	0	231.91	27.74
Steel	51.16	5.37	–	0	51.16	6.12
Aluminium	14.81	1.56	11.66	10.03	3.51	0.42
Copper	10.61	1.12	10.61	9.12	–	0
Zinc	2.25	0.25	2.25	1.94	–	0
Lead	0.72	0.08	0.72	0.62	–	0
Total	952.27	100	116.27	100	836	100

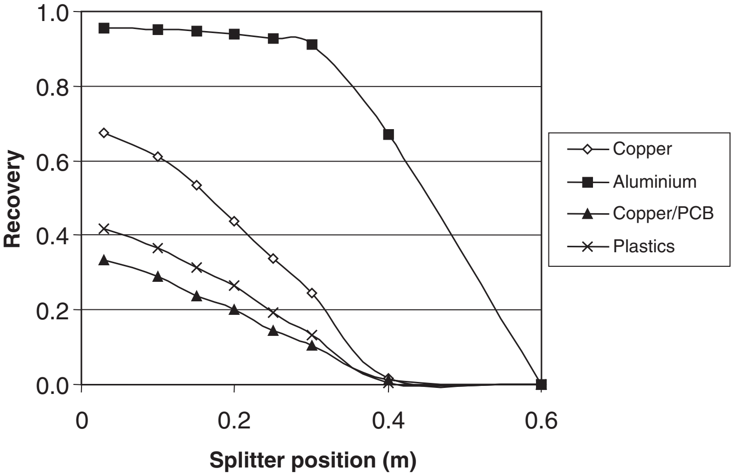

FIGURE 5 Recovery of aluminium, fine copper wire, pieces of copper-containing PCB and plastics in the product as a function of splitter position (horizontal distance from the rotor centre).

the fine copper wires. The remaining mixture contained mostly plastic flakes, polluted with 1.5 mass% of aluminium flakes and 1.1 mass% of very fine copper wires (typically 0.1 mm diameter). The mixture was fed wet over an eddy current separator at the same conditions as in the previous experiments, except for a higher rotor speed of 2000 rpm. The higher rotor speed was selected because the mixture did not contain weakly magnetic materials. Figure 5 shows the recovery of plastics, aluminium and the remaining copper wires as a function of the horizontal splitter coordinate. The results confirm that the separation is effective for metals larger than 1 mm, but not below.

4. CONCLUSION

Non-ferrous metals in the range from 2 to 6 mm can be concentrated at high recovery from waste streams by feeding them slightly wet to traditional eddy current separators that are designed for larger particle sizes. Rotor speeds can be relatively low, due to the fact that the electromagnetic torque is used only to break the wet bond between the non-ferrous particles and the surface of the belt. This has the advantage that weakly magnetic particles remain attracted to the rotor. Results show that high recoveries are obtained also for lead and stainless steel. Part of the success for these materials is probably related to high specific gravity and particle shape. The separation works well at feed rates of 4 t/h per metre width of the separator. Typical moisture content of the feed should be 10–15%. The high recovery of the process is attractive for waste streams that need very low residual concentrations of non-ferrous metals in order to be recycled, such as PET bottles, glass cullet or the fine fraction of shredder residues.

Acknowledgement

The authors thank Miss Marieke Mooij for conducting the trial experiments on the electronics scrap sample.

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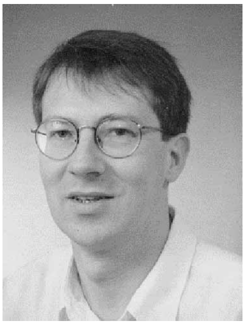
BIOGRAPHIES

Francesca Settimo was born in Trieste in 1977. Presently she is studying environmental engineering at the University of Trieste, Italy. In early 2003 she spent six months at the Department of Applied Science of the Delft University of Technology, the Netherlands.

Paolo Bevilacqua was born in Trieste in 1962. He is the professor of raw material engineering at the University of Trieste. His main areas of interest are ore dressing and recycling process techniques. Professor Bevilacqua is the author of approximately 90 papers. He is a member of the International Committee of Scientific Congresses.



Peter Rem is a research coordinator for the Resource Engineering Section of Delft University, the Netherlands. He studied physics at Leiden University and did his Ph.D. in the field of technical superconductors at Twente University in the Netherlands, before joining the Shell Research Laboratories in Amsterdam. His present interests are in separation technology.