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Review

Environment-friendly technology for recovering nonferrous metals from e-waste: Eddy current separation

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ABSTRACT

The current generation pattern of e-waste consisted of dead electronic and electrical equipments poses one of the world's greatest pollution problem due to the lack of appropriate recovery technology. Crude recovery methods of resource materials (aluminum, zinc, copper, lead, gold) from e-waste caused serious pollution in China in the past years. Thus, environment-friendly technologies have been the pressing demand in e-waste recovering. Eddy current separation (ECS) was advised as the preferable technology for recovering nonferrous metals from e-waste. However, just a few reports focused on the application of ECS in e-waste recovering. This paper introduced the information about ECS including the models of eddy current force and movement behavior of nonferrous metallic particle in the separation process. Meanwhile, the developing process of eddy current separator was summarized. New industrial applications of ECS in e-waste (waste toner cartridges and refrigerator cabinets) recovering were also presented. Finally, for improving separation rate of ECS in industrial application of e-waste recovering, some suggestions were proposed related to crushing process, separator design, and separator operation. The aim of this paper is to demonstrate the effectiveness of ECS technology as practical and available tool for recovering non-ferrous metals from e-waste which is now being ignored.

Contents

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Nomenclatures

b_n	Fourier coefficient
B_m	magnetic flux density of the magnetic drum surface (T)
B_p	induced magnetic flux density in the particle (T)
B_r (B, B^a)	magnetic flux density of the field (T)
F_r	repulsive force between the particle and the magnet (N)
g	acceleration of gravity force (m/s^2)
G	gravity force of the aluminum flake (N)
J (j)	induced eddy current in particle (flakes) (A)
k	pairs of the magnets placed in the magnetic drum
l	height of the rectangle/triangle flake (m)
L	circumference of the triangle flake (m)
r	radius distance between the particle and the center of magnetic drum (m)
r'	radial distance between the particle and the inducing magnet (m)
R (R_{drum})	radius of the magnetic drum (m)
S_m	per magnet side area which facing the flake (m^3)
S_p (d)	maximal cross area of the flake in horizontal (m^2)
t	time cost for the magnetic field rotation (s)
T	thickness of the flake (m)
v (Ω)	feeding speed of the particle (flake) (m/s)
v'	relative linear velocity between the flake and magnetic drum (m/s)
V	volume of the particle (rectangle/triangle flake) (m^3)
w	width of the rectangle/triangle flake (m)
Ω	resistance of circular/rectangle/triangle coil
α_0	angle of the coordinate in the cylindrical coordinate system
γ (τ, σ)	conductivity of the flake (S/m)
δ (s)	oriental (shape) factor of the flake in eddy current separation
ε_i	induced emf in the circular/rectangle/triangle coil (V)
μ_r	relative magnetic permeability of iron (H/m)
μ_0	magnetic permeability of vacuum (H/m)
ω_m (ω_{drum}, ω)	rotation velocity of the magnetic drum (rad/s)
Φ_p	induced magnetic flux in the particle (Wb)
Φ_m	magnetic flux of the permanent magnet (Wb)
$\Delta\Phi$	variation of magnetic flux in the particle (Wb/s)
$w(\lambda)$	width of pole

1. Introduction

Quantities of e-waste are generating resulted from the use of electronic and electrical products. Computer accessories and mobile telephones are disproportionately abundant because of their short lifespan. The current global production of e-waste is estimated to be 20–25 million tons per year and about 95% useful materials were recovered (Robinson, 2009). About 2.5 million tons e-waste appeared in Chinese mainland including self-generated and imported from developed countries per year (Ongondo et al., 2011; Stone, 2009; Widmera et al., 2005). Fig. 1 shows samples of nonferrous metals found in e-waste. Waste PCB contains nearly 28% metals including copper, zinc, and other nonferrous metals (Li and Xu, 2010). Waste toner cartridge has 11.7% aluminum (Ruan et al., 2011). Waste refrigerator cabinet includes about 8.9% copper and aluminum (Ruan and Xu, 2011a,b). Additionally, purity of metals in e-waste is higher than that of rich-content minerals (Laner and Rechberger, 2007; Ilgin and Gupta, 2010a,b). Thus, recovering e-waste can bring great economic benefits.

Environmental sound technologies of recovering e-waste are developing challenges today. In the early stage, crude technologies (acid-washing or open incineration) were employed (Ruan and Xu, 2012a,b; Ilgin and Gupta, 2010a,b) and resulted to serious environmental pollution by the hazardous materials contained in e-waste (Duan et al., 2011; Huo et al., 2007; Leung et al., 2008). Then, for the sake of environmental protection and clean recovery of nonmetals from e-waste, it was proposed a procedure including crushing process and psychical separations of screen, shape sorting, jigging, magnetic separation, air current separation, corona-electrostatic separation, and eddy current separation (ECS) (Zhou and Xu, 2012; Cui and Forssberg, 2003). However, each technology has special limitation. Screen and shape sorting cannot separate the particles that have similar size and shape. Jigging brings waste water in separation process. Magnetic separation can only separate ferrous metals. Air current separation demands particles having great density difference when being in similar size. Corona-electrostatic separation and ECS are the preferable technologies for recovering nonferrous metals from e-waste. Corona-electrostatic is skilled in separating nonferrous metallic particles (NMP) less than 1 mm in size (Wu et al., 2008). ECS is adept in separating NMPs ranged from 2 to 50 mm in size. ECS may be the fittest technology for recovering nonferrous metals from large-scale (coarse crushing is enough for liberating the materials) e-waste (Zhang et al., 2002; Benaboua and Georgesa, 2008).

ECS is an environment-friendly technology for separating nonferrous metals from solid waste. In separation process, eddy current is induced in nonferrous metal when meeting variable magnetic field. Interaction between eddy current and magnetic field changes the trajectory of nonferrous metal as well as separates them from others. No waste water, air pollution, and solid waste are generated in the separation process. Unfortunately, the public paid less attention on this environment-friendly technology.

This paper discussed ECS technology from the models of eddy current force (ECF), models of particle movement behavior, developing of separator, and new industrial application standpoints for e-waste recovering. Furthermore, suggestions for improving separation rate of ECS are presented.

2. Eddy current force and eddy current separation

2.1. Eddy current force

ECS is a physical method for separating nonferrous metals from inert materials. ECF is the cause of ECS. In general, eddy current separator is comprised of magnetic drum. The magnetic drum always consists of magnetic poles placed in N–S–N (see Fig. 2). A changing magnetic field will be induced by the rotation of magnetic drum (Peterson, 2003; Rolicz, 2009). There are two recognitions about the generation of ECF. Recognition (1): eddy current will appear in NMP when it experiences the changing magnetic field; a repulsive force will be generated between magnetic field and NMP possessing eddy current; this repulsive force is called ECF. Recognition (2): direction of the magnetic field changes constantly because of the running of magnetic drum; consequently, the direction of eddy current induced in NMP also changes continuously resulting in the generation of a new magnetic field in NMP; direction of the new magnetic field is also changed constantly; the two magnetic fields have the same directions and repulse each other; this repulsion is called ECF.

Because of being the most important influencing factor of ECS, many models for computing ECF were constructed. The models of ECF established from recognition (1) including: