Finite Element Analysis of Separation Force on Non-ferrous Metals Induced by Eddy Current Separator

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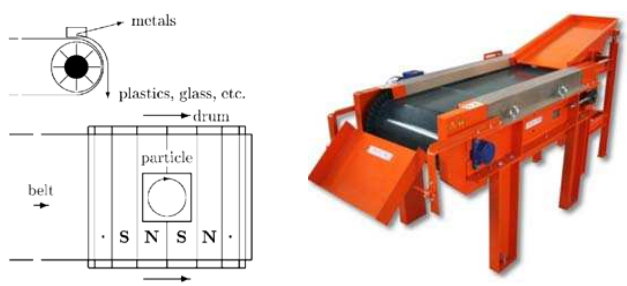
Abstract— Finite element method (FEM) analyses of the eddy current separator (ECS) that can separate non-ferrous metals from waste via the eddy current method have been carried out in this study. The forces induced in the non-ferrous metals to be separated by the magnetic drum determining the performance of the separator have been analyzed according to certain variables. These variables are drum speed, air gap between the material and the magnet pole, dimensions, and conductivity of the material and magnet height. The resultant force has been estimated according to these variables. The increase of drum speed and enlargement of non-ferrous metals, high conductivity and decrease of the air gap have increased the separation force. The ECS design is determined according to the analytical equalities has been verified by these analyses.

1. INTRODUCTION

Eddy current is an effective method for the separation of non-ferrous valuable metals. According to the eddy current principle, an electric charge is induced in the material in accordance with the Faraday's law when the changing magnetic flux is cut off the non-ferrous metal. Eddy currents occur in this materials and magnetic field occurs in the material due to the effect of the eddy currents in accordance with the Ampere's Law. This field is affected from the magnetic field of the magnetic drum. Thus a force is induced in the material as a result of the effect of these two fields interaction in accordance with the Biot-Savart law. The material is thrown from the product flow with the effect of this repellent force. Figure 1 shows the principle diagram [1] and actual photograph for the ECS displaying the separation of non-ferrous metals.



(a) (b)

Figure 1: (a) ECS magnetic drum principle diagram [1], (b) ECS (COGELME™).

ECS is made up of a conveyor band system and a magnetic drum which is the most important part of ECS. It rotates at high speeds under the conveyor band independent of the driving gear of the band. Analyzed drum consist of 36 neodymium magnets which are placed on cylindrical iron surface as NS. Non-ferrous waste metal particles move towards the drum over the belt and fall into the container when they are interacted with the drum field. Thus, separation is completed. Literature survey has put forth that the number of studies on the magnetic analyses of ECS is not sufficient. The studies carried out aim to increase the separation performance in small particles. In Lungu study [2] the separation systems were examined for the small metal particles inside a two component non-ferrous mixture via a permanent magnet new type dynamic ECS. This ECS is also known as angular magnetic drum. This ECS contains permanent magnets and magnetic drum that is arranged as NS. Here, the effect of the angle of the drum in the horizontal position on the separation process has been examined. The experiments carried out using copper and copper aluminum have been successful [2]. Kang and Schoenung [3] have carried out studies putting forth that the main criteria for an eddy current separator are the density of the material ρ, its electrical conductivity σ and the ratio of its density to electrical conductivity σ/ρ. Materials with higher conductivity per density can be separated more easily. It is observed that the separation ratio is higher for small particles in this separation process [3,4]. It has been emphasized that the drum speed and the number of magnetic poles have to be increased in order to increase separation force will attain its maximum value as a result of this increase. In addition, it is also specified that separation efficiency can be increased by adjusting the material input and conveyor band speeds. Experiments have been carried out for the separation of materials from inside an aluminum and plastic mixture with different weights and a dimension of 5 mm by changing the speed of the drum between 10 Hz and 25 Hz and by changing the conveyor band rotational speed between 6 Hz and 12 Hz. It has been concluded as a result of the study that the efficiency is above 98% when the drum rotates at a speed of 25 Hz and the conveyor band rotates at a rate of 8 Hz [3,4].

In this study; parameters that affect the separation performance for ECS design such as drum speed, air gap between the material and the magnet, type and dimensions of the materials have been examined by FEM and the results have been presented in graphs. Thus, it is a guiding study for design corrections.

2. MATERIAL AND METHOD

The most important variables that determine the separator efficiency are the amplitude and frequency of the eddy current. Increase in these variables directly affects separation efficiency since they also change the repellent force. Factors that determine the amplitude of the eddy current, its frequency and the magnitude of the repellent force depend on the material properties and separator design. The factors that depend on material properties are type, density, resistivity, conductivity, shape and dimensions. Whereas parameters that depend on separator design and drum speed, number of poles, magnetic field intensity of the drum and the air gap distance between the drum and the material. The induced current according to Faraday's law of induction in the particle subject to the variable magnetic field has been given in Eq. (1) [1,5]. Here, the magnitude of the eddy current is determined by the rate of change of the magnetic flux with time.

$$\vec{\nabla} x \vec{J} = -\rho \frac{\partial \vec{B}}{\partial t} \tag{1}$$

where J is current density and ρ is the specific conductivity of the particle. The direction of the induction current is determined via Lenz Law. Accordingly, the direction of the induced current is opposite to the field that causes it to occur. These opposite magnetic fields generate a repellent force on the linear surface element (ds) and are represented by Eq. (2) [1,5].

$$\vec{F}_L = I d\vec{s} x \vec{B} \tag{2}$$

Here, I is current induced on the material. F_L force provides the movement of the particle and diverts it. The force that causes separation via eddy current in the material. Wang et al. have expressed the repellent force in the eddy current separator caused by the variable magnetic field of the rotating magnetic drum in a more simplified manner with Eqs. (3) and (4) [4,5].

$$F_r = H^2 f \times \frac{m\sigma}{\rho s} \tag{3}$$

$$f = \frac{np}{2} \tag{4}$$

where F_r represents the repellent force, H is magnetic field intensity, f is magnetic field frequency, n is speed of the magnetic drum, p is number of magnetic poles, m is mass, σ is conductivity and, ρ is density and s is shape factor. The resultant force is related with material properties for different materials. The ratio of conductivity to density (σ/ρ) determines the magnitude of the force and the difficulty of separation. Separation success is higher for materials with a higher ratio [4,5]. The drum has been analyzed by the Ansys-Maxwell software using FEM. Drum speed, the air gap between the material and the drum magnet, the type of material and the size of the material have been examined in these analyses. The analyses carried out have put forth the effects of the axial and resultant forces that are generated on the material in accordance with the parameters given above. The design picture of the magnetic drum with 36 magnetic poles placed on a rotor and its 2 dimensional analysis model have been given in Figure 2. Transient analyses have been carried out for one pole step (from N to S) with high sampling ratio for the rotating motion since the analysis results will be the same for each pole step. To this end, the pole step duration for 2000 rpm speed

Table 1: $NdFe_{35}$ magnet specifications.

Relative permeability	1.0998	H magnitude	890000 A/m
Bulk conductivity	625000 S/m	Max. working temp.	100°C

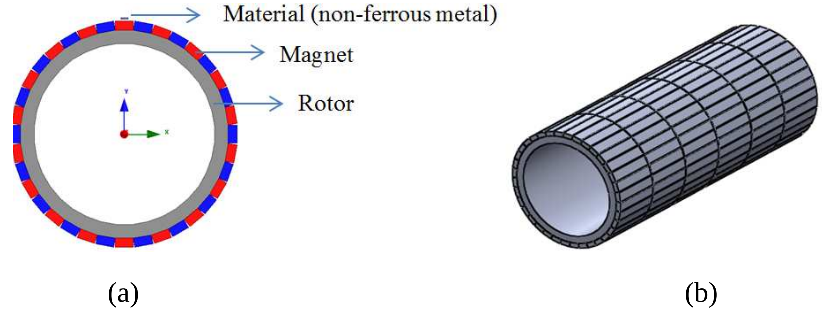


Figure 2: Magnetic drum, (a) 2D analysis model, (b) 3D design model.

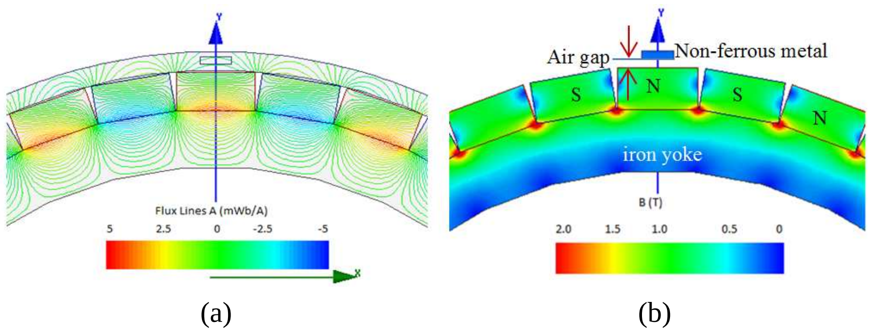


Figure 3: (a) Flux lines, (b) flux density.

is 833 µs. 125 solutions have been made in this time period and analysis results have been attained. Similarly, the results of the axial forces and resultant force on the material have been estimated for 2000–6000 rpm speeds with a high accuracy.

There are 36 magnet poles on the drum surface placed adjacent to each other as NS. The magnet specifications of these magnets have been given in Table 1.

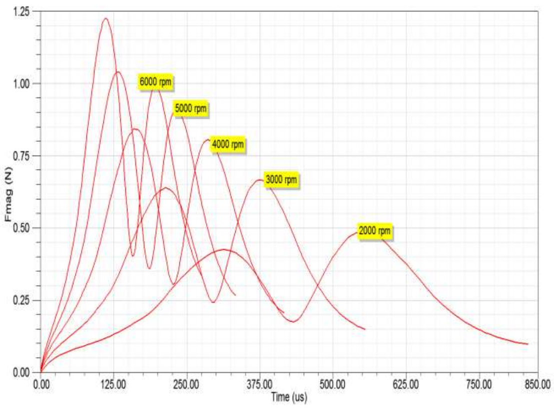
3. FEM ANALYSES

Visual results that put forth the flux lines and the distribution of magnetic flux density in magnetic analyses have been given in Figure 3. It is observed that flux lines circle the material and that saturation occurs at the magnet corners.

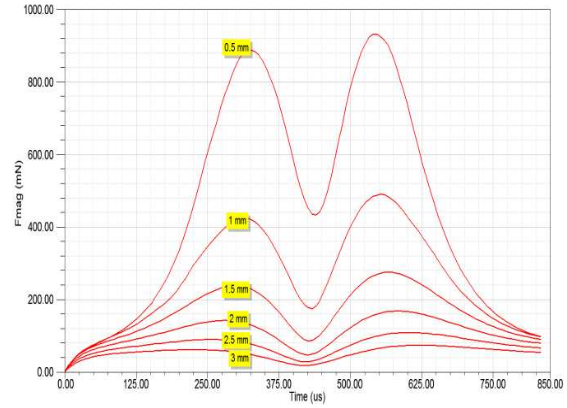
All parameters excluding speed have been kept constant in order to examine the effect of speed on the forces that are generated on the material. During the analyses, a copper material with a height of 1 mm, width of 4 mm, and length of 10 mm has been placed on the drum. The horizontal, vertical and resultant forces on the material for drum speed values between 2000–6000 rpm have been examined. The resultant force according to speed have been given in Figure 4(a). According to the analysis results, the forces on the material verify the expressions given in Eqs. (3) and (4). It is observed that the period decreases, frequency and force increases with increasing speed.

The analyses carried out have targeted to determine the effect of the air gap on the eddy currents and thus the forces on the material. To this end, the material has been analyzed for air gap values between the material and the drum of 0.5, 1, 1.5, 2, 2.5 and 3 mm at a constant drum speed of 2000 rpm. The resultant force on the material has been given in Figure 4(b).

Magnetic reluctance increases in the air gap since magnetic flux permeability is low. Magnetic flux is inversely proportional with reluctance in a magnetic circuit. Magnetic flux that peneterate the material to be separated decreases when the air gap increases. According to the analyses results, the resultant force on the material increase when the air gap decreases. When the average value of the resultant force is considered, the force is approximately 53 mN for the case when the air gap is 3 mm and the air gap is 0.5 mm for the case when the force is 460 mN.

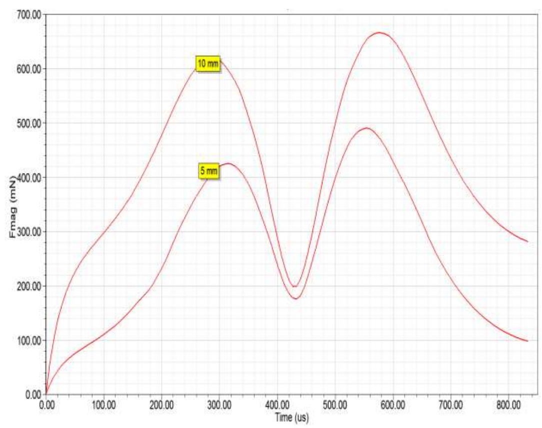


(a)



(b)

Figure 4: Resultant forces on the copper material, (a) vs. speed, (b) vs. air gap.



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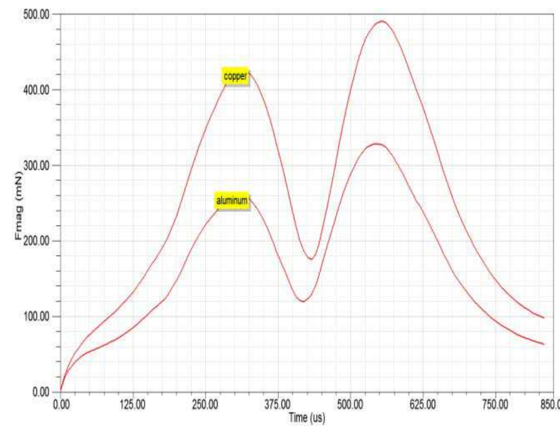
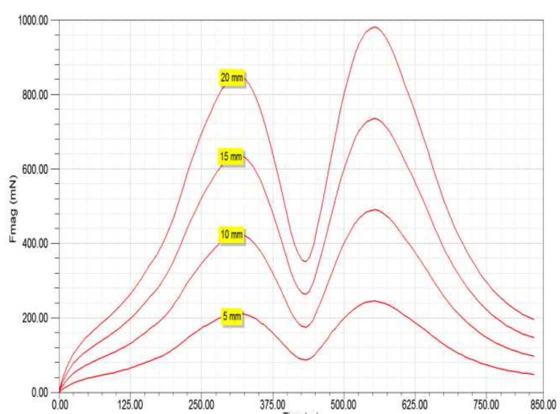


(b)

Figure 5: (a) Resultant forces acting on the copper material for different magnet dimensions, (b) resultant forces on aluminum and copper material.



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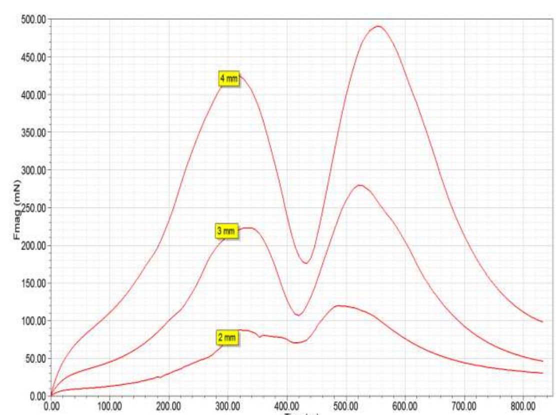

(b)

Figure 6: Resultant forces acting on the copper material, (a) vs. material length, (b) vs. material width.

Forces have been examined only for copper and aluminum during the analyses keeping all other parameters constant. The resultant force have been given in Figure 5(a). Since the specific resistance and density of the material changes according to the material type, the eddy current and force also changes. The force on materials with higher conductivity is higher.

The dimensions of the magnet have been kept constant at width of 10 mm and height of 50 mm and height of 5 and 10 mm and analyses have been carried out. The resultant force acting on the material have been given in Figure 5(b).

The dimensions of the copper material have been kept constant at width of 4 mm and height of 1 mm and height of 5, 10, 15 and 20 mm and analyses have been carried out. The resultant force acting on the material have been given in Figure 6(a). The dimensions of the copper material have been kept constant at height of 1 mm and length of 10 mm. Variables are material width of 2, 3 and 4 mm analyses have been carried out. The resultant force acting on the material have been given in Figure 6(b). As can be seen from the graphs, the area of the material overlapping the magnetic surface increases with increasing material dimensions. Thus, eddy currents and the forces acting on the material also increase.

4. CONCLUSIONS

Non-ferrous materials are separated by ECS. According to Faraday, Ampere and Biot-Savart laws a repellent force is induced on non-ferrous material by the effect of eddy current. This force determines separation performance. The factors that affect the performance of this separation depend on the material specifications and the design of the ECS. Significant factors depend on metal conductivity, density and dimensions of the material. The variables that depend on design are drum speed, number of poles, the air gap, magnetic field intensity and magnet height. FEM analyses have been carried out for the variables are drum speed, air gap, magnet height, material type and dimensions. The increase of drum speed, material dimensions and magnet height, high conductivity of the material and decrease of air gap have increased the separation force and performance. Proposed magnetic drum design has been verified according to the obtained from these analyses.

ACKNOWLEDGMENT

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