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Performance Determination of Novel Design Eddy Current Separator for Recycling of Non-Ferrous Metal Particles

Ahmet Fenercioglu[1]* and Hamit Barutcu[2]

Department of Mechatronics Engineering, Gaziosmanpasa University, 60250, Tokat, Turkey

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Improvements were made in the study for the design of the conventional Eddy Current Separator (ECS) used for separating small sized non-ferrous particles in the waste. These improvements include decreasing the air gap between the material and magnetic drum, making the drum position adjustable and placing the splitter closer to the drum. Thus, small particles were separated with high efficiency. The magnetic drum was removed from inside the ECS conveyor belt system as design change and was placed as a separate unit. Hence, the force generated on the test material increased by about 5.5 times while the air gap between the non-ferrous materials and drum decreased from 3 mm to 1 mm. The non-metal material in the waste is separated before the drum in the novel design. Whereas non-ferrous metal particles are separated by falling into the splitter as a result of the force generated as soon as the particles fall on the drum. Every material that passes through the drum can be recycled as a result of moving the splitter closer to the contact point of the drum. In addition, the drum can also be used for the efficient separation of large particles since its position can be adjusted according to the size of the waste material. The performance of the novel design ECS was verified via analytical approaches, finite element analysis (FEA) and experimental studies.

Keywords : eddy current separator, finite element analysis, non-ferrous metal recycling

1. Introduction

ECS are machines consisting of three separate units that separate valuable non-ferrous metals such as copper, aluminum from among wastes. These are the conveyor belt, feeding unit and magnetic drum. The feeding unit is a vibratory system that enables the proper distribution of the waste material on the belt by placing them on the conveyor. The conveyor belt carries this material onto the magnetic drum. Whereas the magnetic drum is made up of permanent magnet poles rotating at high speeds in a mechanical isolation sheet. An eddy current is induced in the metal passing over the drum in accordance with the Faraday Law. A magnetic field is generated in the metal particle due to this current and thus a force is generated when the particle enters the effect area of the varying magnetic field of the drum. The metal is thrown out with the effect of this force and falls into the splitter cup. Non-metal materials fall into the other cup with the effect of gravity. The conventional working principle and industrial application of the ECS have been shown in Fig. 1.

Academic studies on ECS are quite limited even though they have an important place in the field of recycling technologies. Majority of the recent studies published include ECS designs that can separate mostly small particles.

The literature [1] examined the separation success of rotating ECS used to separate valuable metals at the particle size following the breaking down of electric-electronic products that have completed their service lives. Different ECS designs were examined for the separation of non-metal valuable metals smaller than 5 mm as well as copper cable parts. The 1st section of the study focused on rotating ECS that is widely used in our day. Whereas various experiments were carried out in the 2nd section for the separation of electronic wastes via wet ECS technology. The experiments carried out to separate the aluminum particles in electronic wastes were successful [1]. Studies were carried out as part of literature [2] on the modeling of the magnetic propulsion force of ECS. It was put forth that the separation of various materials via eddy current is not dependent only on the force that deflects the material thus calculating the gravity and

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*Corresponding author: Tel: +90 530 348 6345
Fax: +90 356 252 17 29, e-mail: ahmet.fenercioglu@gop.edu

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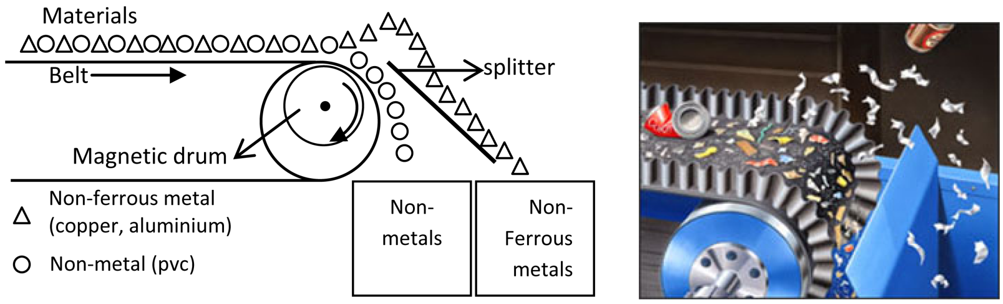


(a) (b)

Fig. 1. (Color online) Conventional ECS (a) working principle (b) industrial application (K.W. Supply).

centrifugal force on the material and analyzed the force generated on the particle on the drum [2]. Computer aided design, simulations, modeling and analyses of ECS were carried via the effective use of computer technology thus taking important steps for the development of the design [3]. Literature [4] put forth a new method that uses electromagnetic sensors for the separation of non-ferrous waste metals via eddy current method and for defining the metals. Non-ferrous metals were separated as copper, bronze and stainless steel according to their types via this sensor on a prototype system [4]. Literature [5] carried out a study in which the separation method for the small metal particles via new dynamic ECS with permanent magnet was examined from inside the non-ferrous two component mixture. This is also named as ECS with angular drum. The effect of the drum angle on the separation process was examined by changing the drum angle on the horizontal. Experiments carried out with copper, lead and aluminum were also successful [5]. In the literature [6]; Kang and Schoenung carried out a study in which the main criterion for ECS separation was put forth as the ratio of ρ material density to σ electrical conductivity (σ/ρ). Materials with higher ratios can be separated more easily [6]. Literature [7] presented a study in which various experimental studies were carried out on the type known as the most efficient ECS type in which the magnetic drum rotates on the horizontal axis. It has been emphasized that the speed of the magnetic rotor and the number of magnetic poles should be increased in order to increase magnetic flux frequency and that the separation force will reach its maximum value as a result of this increase. In addition, it has also been stated that separation efficiency increases as a result of the adjustment of the speed of material feeding and conveyor belt. It was concluded as a result of the experiments carried out for the separation of non-ferrous metal material from among aluminum and plastic mixture waste at 5 mm dimension and various weights that efficiency is above 95 % when the magnetic rotor speed is 25 Hz and the conveyor belt speed is 8 Hz [7]. Literature [8] focused on the analysis of this new ECS via finite element method (FEM). The forces induced by the magnetic drum on the material to be separated were determined according to different variables as a result of simulations carried out to verify the performance of the splitter prior to design. Separation force increased with drum speed increase, air gap decrease, increase in the number of poles, increase of material size and selection of materials with high conductivity [8]. In [9] the separation performances of granule power cable wastes with diameters of 1.5-2 mm and lengths of 4-5 mm were examined experimentally. It was determined as a result of the experimental measurements carried out at belt speed of 0.2 m/s, drum speed of 3,000 rpm that separation success was 94.7 % for copper, 99.5 % for aluminum and 97.8 % for the mixture with this new ECS [9].

Changes in ECS design have been made in this study which are different in comparison with those in the relevant literature and the conventional system. The drum was placed in front of the conveyor as a separate unit the position of which can be adjusted. Thus, the gap between the material and the drum decreased since the belt was removed. Non-metal materials fall first from the drum in this system and since these wastes do not pass beyond the drum, the splitter has been brought as close to the drum as its point of contact. Thus, separation efficiency was increased. The design was verified via analytical approaches and FEA and the performance was determined as a result of the experimental studies carried out with the prototype. Hence, it was possible to separate granule sized small particles.

2. Material and Method

The operating principle of ECS is based on the force produced by the magnetic force generated by the eddy current induced in the conducting material. This principle is based on the Faraday, Ampere and Biot-Savart laws. An electromotor force is generated in the conducting material that is subject to the magnetic field of the rotating drum which can be given as Eq. (1). The magnitude of this force is equal to the change of the magnetic flux with time.

$$e = -\frac{d\Phi}{dt} \tag{1}$$

The direction of the induced current is determined by the Lenz law. According to this law, the direction of the current is opposite to the force that generates it. The current induced in the particle subject to variable magnetic field according to the Faraday induction law has been given in Eq. (2). The magnitude of the eddy current is determined by the change of magnetic flux density with time.

$$\vec{\nabla} \times \vec{J} = -\rho \frac{\partial \vec{B}}{\partial t} \tag{2}$$

Here, J denotes the current intensity (A/m^2), B represents the magnetic flux density (T) and ρ is the conductivity of the material. The current induced in the material generates a magnetic field in the conductor in accordance with Ampere's Law. This field interacts with the drum magnetic field thus generating a Lorentz force in the material as a propulsion force. The Lorentz force is a force that is acted on a point charge by electromagnetic fields. This force is calculated in terms of electrical and magnetic fields via Eq. (3).

$$\vec{F} = q(\vec{E} + v \times \vec{B}) \tag{3}$$

Here, F denotes the force, v represents the instantaneous velocity of the particle and B is equal to the vector of the magnetic field. These opposing magnetic fields generate the Lorentz force represented by Eq. (4) on a linear surface element (ds) of the conductor:

$$\vec{F} = Id\vec{s} \times \vec{B} \tag{4}$$

Here, I is the current that passes through the conductor. This force makes the particle move and diverts it from its path. Literature [7] expressed the force generated by the variable magnetic field of the rotating magnetic drum in the ECS in a more simple manner via Eq. (5) and (6) [7].

$$F_r = H^2 f \times \frac{m\sigma}{\delta s} \tag{5}$$

$$f = \frac{np}{2} \tag{6}$$

Here, F_r represents the propulsion force, H represents the magnetic field intensity, f represents the magnetic field frequency, n represents the speed of magnetic drum, p represents the number of magnetic poles, m represents mass, σ represents conductivity, δ represents the form and density factors of the material. 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 level of difficulty of the separation. Success of separation is greater in materials for which this ratio is higher [7].

As can be seen from the equalities, there are many parameters that affect the force. Some of these parameters are related with ECS design whereas the others are related with the material to be separated. The parameters related with design are the magnetic flux density that circles the material and the frequency of this flux. Whereas the variables that affect the magnetic flux density are the magnetic field densities of the magnets and the air gap between the material and the magnet. The variables that affect the frequency are the number of poles of the magnet and the speed of the drum. The parameters related with the material are specific resistivity, density and the dimensions of the material. Separation force increases with increasing magnetic field density, number of poles and speed of the drum. Separation force increases with

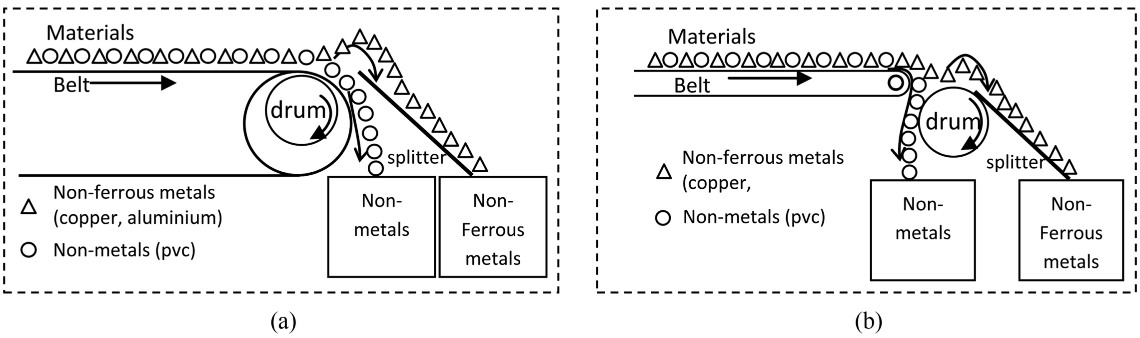


Fig. 2. Working principle (a) conventional ECS (b) new design ECS.

decreasing air gap distance and increasing specific resistivity.

The novel design ECS is made up of 3 independent units. These are the magnetic drum, the belt system and the feeding unit. Magnetic drum is the most important part that affects separation performance. It generates eddy current and force on the material. The feeding unit loads the waste material onto the conveyor belt. The conveyor is a rolling belt with adjustable speed that carries the wastes to the drum. In conventional ECS applications, the magnetic drum is fixed inside the rolling belt. Whereas in the new design ECS, the magnetic drum is placed in front of the conveyor as a separate unit the position of which can be adjusted in two axes. The working principles of the conventional and novel design ECS have been given in Fig. 2.

The most important differences that affect performance in the novel design ECS are the proximity of the splitter to the drum, the narrowing of the gap between the drum surface and the material and the adjustability of the drum position. The prototype ECS was designed to separate 250 kg granule copper waste per hour. It has been shown in Fig. 3.

2.1. Analysis and Experimental Setup

Theoretical approximations can be used depending on some assumptions such as linearity, uniform field and non-saturated core etc. in magnetic problems. Thus, analytical method is not sufficient by itself for magnetic design procedures. FEM analysis is a reliable verification tool. The analysis was made via ANSYS Maxwell™ 2D transient platform to verify design. Test material was placed on the magnetic drum with air gap. The magnetic drum was rotated 20 degrees from N to S poles since the remaining rotation pattern is the same. Force data was obtained in this interval according to speed and air gap variations. Analysis model is shown in Fig. 4.

Experimental setup is given in Fig. 5. The force is measured using a dynamometer. Test material was roped and fixed on the magnetic drum. The movement of the material was force stopped using the dynamometer with rope and at that moment F_x force was measured according to drum speed and air gap distance.

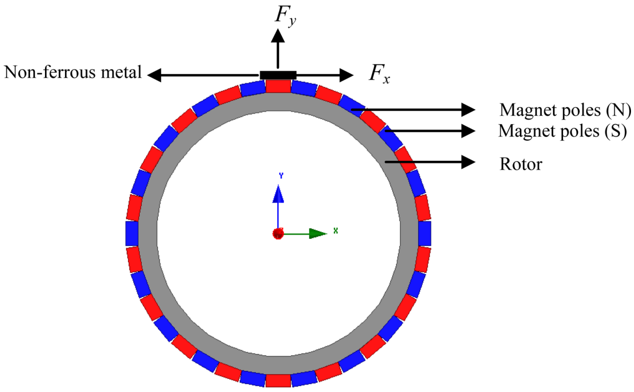


Fig. 4. (Color online) Magnetic drum 2d analysis model.

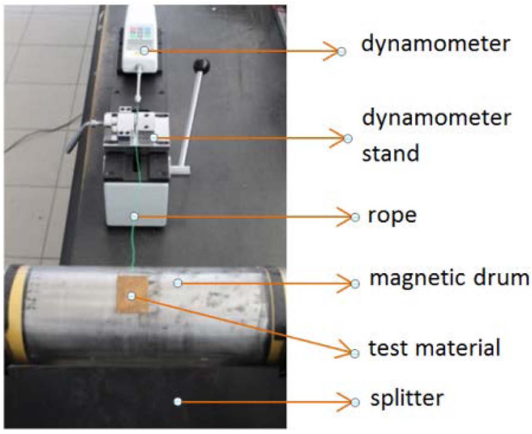


Fig. 5. (Color online) Measuring the F_x force induced on material.

Efficiency experiments were made for the separation of granule cables waste which has been given in Fig. 6. Granule power cable sizes are about 1.5 mm diameter and 4-5 mm length resembling rice. Experiments were made for copper, aluminum and mixed waste. Granule power cables were weighed before separation, after which PVC was mixed with cable granules and separated via novel

Fig. 3. (Color online) Prototype ECS.

(a) (b)

Fig. 6. (Color online) Granule cable waste (a) mixture cable waste with pvc (b) granule cable.

ECS. Following the separation, cable granules were re-weighed and compared with the weight before separation. Therefore efficiency was calculated experimentally. PVC waste was not included in the calculation since all PVC particles in the waste fell into the other cup due to the effect of gravity.

3. Results and Discussion

Novel ECS performance results were obtained from FEA and experiments. Effects on performance were examined in accordance with proximity of the splitter, decreasing the air gap, adjustable drum position, number of magnet poles, drum speed, magnet volume and material type.

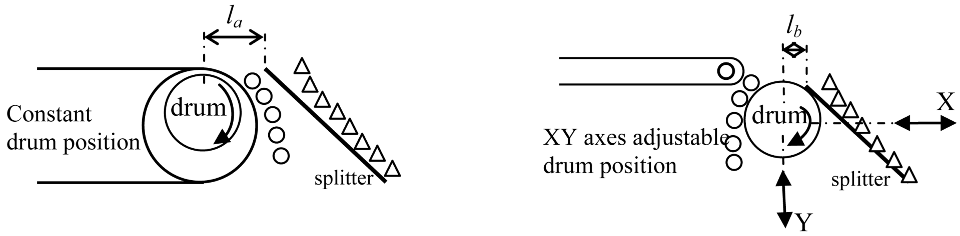
3.1. Effects of the proximity of the splitter to the drum

In conventional ECS, materials are separated after passing through the drum. In this case, non-metal wastes fall down after the drum. A gap has to be left between the splitter and the drum in order to ensure that this falling action takes place. Efficiency decreases in the separation of small particles since this gap increases the path of the material. Whereas there is no need for such a gap after the drum since non-conductive waste materials fallen down before the drum. Hence, the splitter has been placed close to the drum so as to contact it. Figure 7 compares the position of the splitter in conventional and novel design ECS.

Here, l_a represents the distance between the splitter and the center of the drum in conventional ECS, whereas l_b represents the same distance for the novel ECS and $l_b < l_a$. Non-ferrous metals in the waste can be separated by falling onto the splitter due to the effect of the force generated by the eddy current. In conventional ECS, the force generated is not sufficient to enable the small particles to cover this distance since the splitter is further away. The magnetic drum position is adjustable in the new ECS and it has been placed as an independent unit in front of the conveyor. Non-ferrous wastes fall down into a container before the drum. Hence, the distance that the material covers has been minimized by placing the splitter in contact with the drum. The material is diverted from its path via a small force generated on the non-ferrous metals that fall onto the drum and hence they drop down onto the splitter after which they are separated. Thus, it is possible to separate small sized metals that can pass through the drum.

3.2. Effects of moving the material closer to the drum (decreasing the air gap)

The drum is located inside the conveyor in conventional ECS. These two moving systems may operate at different speeds and in different directions inside the same mechanical structure. In this case, the distance between the drum surface and the material increases since the mag-



(a) (b)

Fig. 7. Distance between splitter and drum (a) conventional ECS (b) new design ECS.

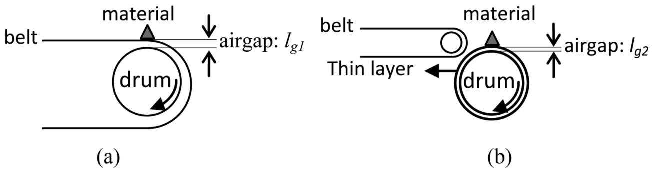


Fig. 8. Airgap between drum and material (a) conventional ECS (b) new design ECS.

netic drum is located inside the rotating cylinder. There is a belt between the magnetic pole and the material. Thus, magnetic reluctance increases due to increasing air gap distance. Therefore, the magnetic field effect of the magnet on the material decreases. The belt is removed in the new design since the drum is used as a separate unit and the material is brought very close to the drum surface. The drum is covered with a thin film layer that does not contact the drum in order to isolate the drum movement and its wind. The material falls directly onto this surface and the maximum air gap is 1 mm. The air gaps between the material and the drum for conventional and novel design ECS are shown in Fig. 8.

Here, the air gap of ECS is shown by l_{g1}, whereas the air gap of the novel design ECS is l_{g2} and $l_{g1} > l_{g2}$. As is given in Eq. (7), air gap reluctance (R) depends on the length of the air gap (l_g), magnetic permeability of the air (m_0) and the flux path cross-section (A_0).

$$R = \frac{l_g}{\mu_0 A} \tag{7}$$

Reluctance (magnetic resistance) increases with increasing air gap l_g and magnetic flux (ϕ) decreases. This has been expressed by the Maxwell equations given in Eq. (8).

$$Hdl = \phi R \tag{8}$$

Accordingly, force decreases. In addition, the effect of air gap on the force has been given in Fig. 9.

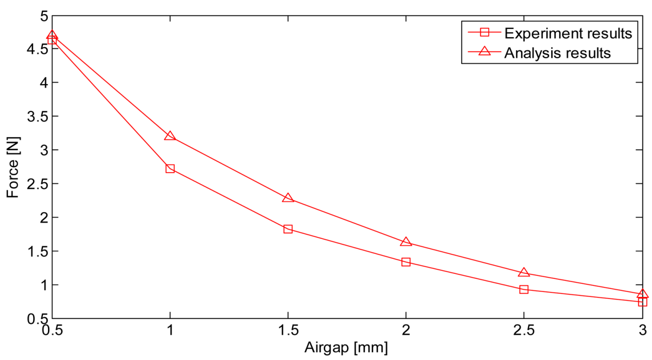


Fig. 9. (Color online) Effect of air gap on the resultant force for the test copper material, analysis and experiments results.

The FEA solutions are given in Fig. 9. The resultant force that is generated on the copper material with dimensions of 30×1×10 mm when the drum is rotated at a speed of 2,000 rpm. Whereas the average value of the force (F_x) is about 166 mN when the air gap is 3 mm, it becomes 913 mN when the air gap is 0.5 mm. Figure 9 indicates the force measured on the material during the experiments carried out under the same analysis conditions according to the air gap. Here, the drum speed has been adjusted as 2,000 rpm and same copper material has been used for this experiment. The air gap was increased by 0.5 mm during the experiment and the effect of the air gap on the force was tested up to 3 mm.

3.3. Effects of the position of the adjustable drum

The drum rotates at a fixed position inside the conveyor belt in conventional ECS. Whereas the position of the drum can change in the X and Y axes in new design ECS. Figure 10 shows the position of the drum.

The effects of the changes in the x and y axis positions on efficiency acquired as a result of the experiments carried out for the waste granule material from aluminum and copper power cable scraps have been given in Fig. 11.

The effects given here are those that are due to the different design of ECS. Experiments have been carried out to determine the effect of the drum position on performance. The drum speed was kept constant at 2,000 rpm, belt speed at 0.3 m/s during the experiments. The amount of material separated for the 0, 1 and 2 cm positions of the drum on the X axis has been determined when the drum was at −2 cm on the Y axis. The results have been given in Fig. 11(a). The drum was kept at X=0 position during the other experiment. Separation process was carried out for the −2, −3 and −4 cm positions of the drum on the Y axis and efficiencies were examined. The acquired results have been given in Fig. 11(b). High efficiency is obtained here for small materials at positions

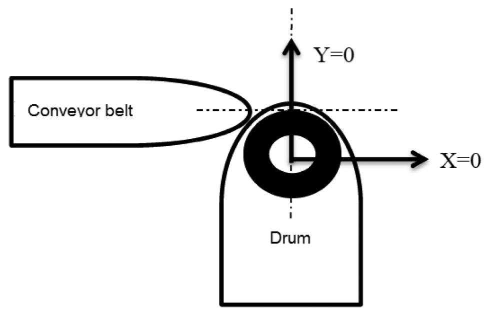


Fig. 10. X=0, Y=0 position of the drum in the novel design ECS.

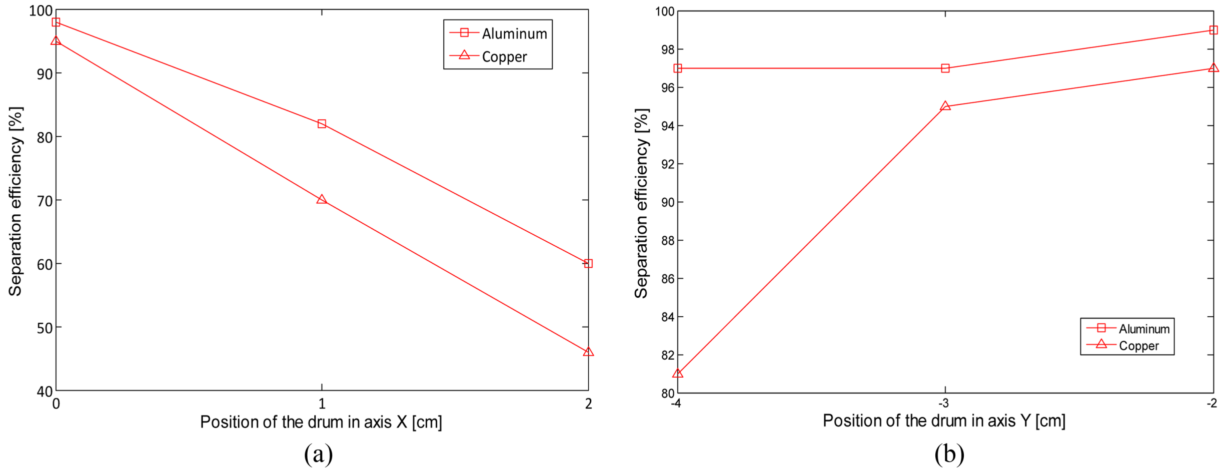


Fig. 11. (Color online) Effect of drum position on efficiency (a) x axis, (b) y axis.

of the drum which are closest to the outlet of the conveyor to where the material drops. Non-metal wastes such as PVC etc. can drop down from the narrow gap between the drum and the conveyor especially for shredded wastes since the material is in granule form. In this position, the kinetic energy that forms in the material is lower since the metal material falls from a closer distance and thus it can easily divert the material from its path. If the size of the material to be separated changes, it will also be possible to separate wastes with different dimensions by adjusting the position of the drum. The gap should be widened especially to be able to separate larger materials and to ensure that the other wastes fall down the gap between the drum and the conveyor. However, it has been determined as a result of the experiments carried out that separation efficiency decreases as the small materials get farther away from the conveyor outlet.

3.4. Effects of the number of poles of the drum and speed

The expression given in Eq. (5) and (6) according to the Faraday Law show the effect of frequency on eddy current. The rate of change of the magnetic field affects the eddy current and the amplitude of the force. There are 2 factors that affect frequency. These are the drum speed and the number of poles. There are 36 magnet poles in the prototype ECS. The frequency of the magnetic field and the generated eddy current for a speed of 2,000 rpm is calculated via Eq. (6) as 600 Hz. According to the experimental studies and analyses carried out to separate shredded power cable wastes, the effect of drum speed on force and separation efficiency has been verified [9]. The air gap was kept constant at 0, 5 mm in order to examine the effect of drum speed on the forces that are generated on

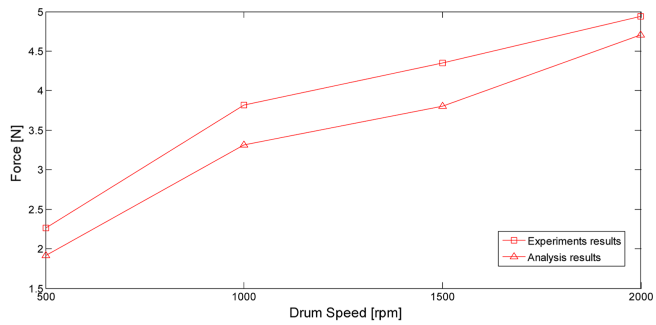


Fig. 12. (Color online) Analysis and experiment results of effect of drum speed on force.

the material. A copper material with a height of 1 mm, width of 10 mm, length of 30 mm was placed during the analyses on the magnetic drum that was designed with 36 poles. The FEA solutions of the resultant force generated on the material for the drum speed interval of 500-2,000 rpm have been given in Fig. 12. Whereas Fig. 12 shows the experimental study results that indicate the effect of the drum speed on the force generated on the material. The air gap was kept constant at 0.5 mm during this experiment. The material used was copper with the same dimensions. The forces generated on the material have been given for the values of the drum speed that vary between the 500-2,000 rpm interval.

3.5. Effects of magnet volume

Magnetic drum consists of N35 neodymium magnet poles. Analyses were carried out by varying the magnet height while keeping all other parameters constant in order to examine the effect of magnet dimensions on force. Accordingly, drum rate and air gap were selected as 2,000 rpm and 0.5 mm respectively. Copper with dimen-

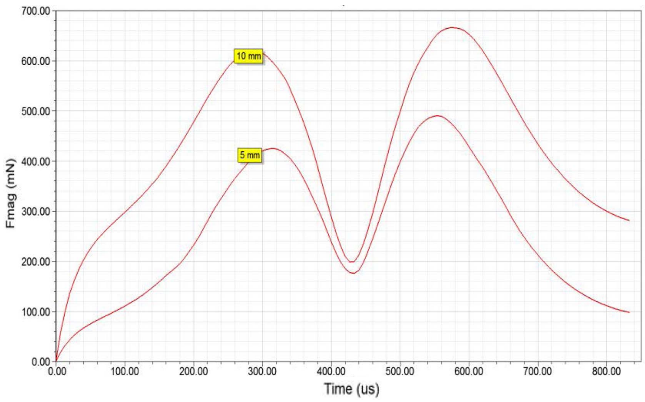


Fig. 13. (Color online) Effects of magnet volume.

sions of 5×1×10 mm was used as the material. Analyses were carried out for cases when the magnet height was 5 and 10 mm and the resultant force acting on the material was given in Fig. 13.

Average value of resultant forces are 428.17 mN for 10 mm and 258.84 mN for 5 mm magnet height. The effect of this parameter was not examined experimentally. However, it was determined analytically that the increase of magnet volume increases the induced current in the material according to the Ampere's Law given in Eq. (9).

$$Hdl = I \tag{9}$$

Here, the current and the resulting force increases since the magnet height (l) is affected. Visual results that put forth the flux lines and the distribution of magnetic flux density in magnetic analyses have been given in Fig. 14. It is observed that flux lines circle the material and that saturation occurs at the magnet corners [8].

3.6. Effects of material type

Eddy current is generated according to the resistivity of the material. The induced current and force increases with decreasing material resistivity. Hence, the force induced

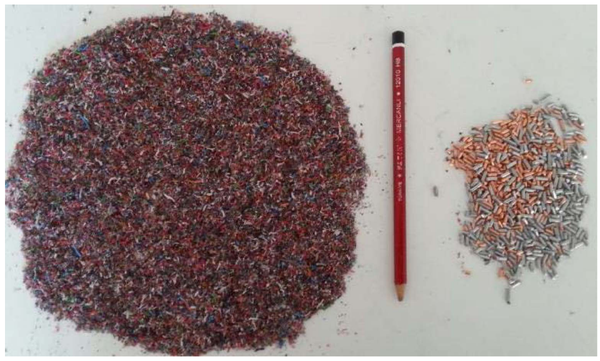


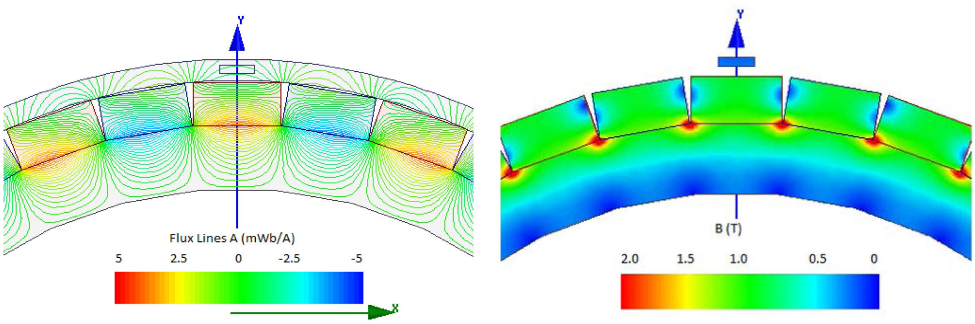
Fig. 15. (Color online) Granule cable waste separation results.

in the material with lower resistivity and higher conductivity is greater. Analysis and experimental results of F_x force values are given in Table 1 for drum speed of 2,000 rpm.

As can be seen from Table 1, the force induced in the copper material is greater in comparison with that in aluminum. However, this result is different in efficiency experiments. The experimental measurements carried out at belt speed of 0.2 m/s, drum speed of 3,000 rpm that separation success was 94.7 % for copper, 99.5 % for aluminum and 97.8 % for the mixture with this novel ECS [9]. The reason for this was explained by Kang and Schoenung in [6]. It was put forth that the main criterion for an ECS for separation is the ratio of the material density ρ to the electrical conductivity σ (σ/ρ) [6]. Materials for which this ratio is greater can be separated more easily. The induced eddy current and force are greater for copper since its conductivity is higher in comparison with aluminum. However, aluminum was

Table 1. Analysis and experimental results of F_x force values

50 × 30 × 1 mm	Copper	Aluminum
Experiment results	4.938 N	3.235 N
Analysis results	4.768 N	3.080 N



(a) (b)

Fig. 14. (Color online) (a) Flux lines, (b) flux density.

separated more easily since its density was lower than that of copper. Separation result is demonstrated in Fig. 15 for mixture waste [9].

4. Conclusion

The separation of non-ferrous small sized particles via ECS is a significant problem. The objective of studies carried out until today on ECS are generally the separation of small particles. Whereas in this study, design changes were made in conventional ECS in order to separate small particles and it was called "novel design ECS". Magnetic drum was removed from the conveyor belt system and was placed in front of the conveyor as an independent unit in this novel design. Thus, only non-ferrous materials can pass from the drum since the non-conducting materials in the waste to be separated fall down first from the drum. Hence, the splitter can be brought in contact with the drum and thus the materials that pass the drum are separated by sliding from the splitter. Thus, a small force is sufficient to divert the non-ferrous metal particle from its flow and separate it. Another novelty is the removal of the band between the non-ferrous metal and magnetic drum. Hence, magnetic reluctance decreased since the air gap between the point where the material touches the drum and the magnet pole decreases. Thus, separation force was increased since the magnetic flux that generates the ring flux on the material as well as the eddy current increases. In addition, the fact that the drum position is adjustable enables the separation of materials with different dimensions. The drum was brought to the closest position with the belt in order to be able to separate small particles. It will be sufficient to increase the gap between the drum and the conveyor for separating larger particles. Small particles were separated with high success via analytical approaches, FEA solutions and the design changes made in accordance with data acquired from the experiments carried out. 99.5 % of the aluminum wastes, 94.7 % of the copper wastes and 97.8 % of the mixed wastes were separated during the experiments carried out with power cables in granule form [9]. In addition, the effects of drum speed, magnet volume, material type and width were also examined in order to determine the performance of the new ECS. The induced force increases with increasing drum speed, magnet height, material conductivity and width. The acquired results were predicted via analytical approaches and verified via FEA solutions and experimental studies.

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