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Scrap stainless steel detection using a pulsed electromagnetic field

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Abstract

A pulsed electromagnetic sensor (PEMS) utilising the difference in electrical and magnetic properties of metals was designed for automatic sorting of scrap stainless steel (SS). Experimental results for the identification and separation of stainless steel are presented. The design of a prototype being developed at Delft University of Technology and the results obtained in the laboratory are also discussed.

Keywords: sorting; scrap metals; pulsed electromagnetic field; eddy current

1. Introduction

The separation of stainless steel (SS) from non-ferrous metal mixture is important not only due to the intrinsic value of scrap SS, but also because it is a contaminant in non-ferrous metal production. For most recycling plants, SS is currently removed from scrap metal by manual sorting. Despite the fact that this is labour intensive, manual sorting is still applied and has to be carried out in low cost countries. It has limitations in capacity per person but the products obtained have acceptable quality and labour is easy to get. Above these all manual sorting may have negative consequences on the human health.

Recently, new methods have been investigated for sorting of scrap metal on a belt or in free fall that use sensors based on several operational principles (de Jong et al., 2000; Nijkerk and Dalmijn, 2001; Gesing et al., 2002). For the identification process, a contact-free sensor must be used, because of the fact that the particles have an irregular shape and size must be taken into account. For automated systems, the particles have to be inspected one-by-one while moving on a conveyer belt across the sensor. After inspection and data processing, an ejection mechanism removes the identified particles from the feed.

Separation systems that use cameras are widely applied in sorting applications. Some examples are from the food industry and metal sorting. Based on differences in the colour, such systems can differentiate between copper and brass (Gesing et al., 2000). However, contaminants, plating and paint on

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the particle surface will lead to identification errors. Usually, the metals have to be washed before the separation in order to remove dirt and improve recovery. Additionally, the applied cameras need special DC-lighting systems and powerful data-processing units for optimal results.

Another application is the removal of SS from a mixture of non-ferrous metals based on colour sorting. This process needs several steps to obtain a sufficient grade and recovery, and it is therefore costly (Kumar et al., 1996). The complication is that the colour of SS is similar to many other metals, such as magnesium, aluminium alloys, zinc, etc. Apart from colour sorting, one of the most advanced systems in automatic sorting of metals and alloys is Laser Induced Breakdown Spectroscopy (LIBS) (Los Alamos, 1982; Mutz and Pretz, 2004). The major disadvantage is that the analysis is sensitive to the composition of metal surface. The LIBS system has been further developed and introduced in industrial applications for automatic sorting of aluminium alloys by Huron Valley Belleville USA (Gesing et al., 2000).

Metal detectors are extensively used for the removal of metal particles from a mixed stream, e.g., for food, agricultural products, glass cullet and other applications (Dalmijn et al., 1995). These systems are based on inducing eddy currents into the metals. The interaction between the particle and the electromagnetic field is measured by sensing elements. Although many applications were studied in the field of metal detection, little research has been conducted for the identification of scrap metals based on their electrical and magnetic properties.

New sensor design using the eddy current principle was studied at Delft University of Technology for the characterisation and differentiation between scrap metals. New methods for metal characterisation in a material flow with pulsed eddy currents were studied and practical solutions were proposed for industrial applications. The main application of the designed system is the identification and separation of non-ferrous scrap originating from end-of-life cars, household appliances, electronic devices or municipal waste. The present investigation focuses on identification and sorting of scrap SS. Although a number of electromagnetic automated sorting systems for scrap metals have entered the market with some success, no information is currently available regarding the system efficiency. In most of the applications, such systems are applied to recover SS from non-metals in combination with a colour camera (Harbeck, 2004). The pulsed electromagnetic sensor (PEMS) proposed in this paper is applied to differentiate and sort out scrap SS from a mixture of non-ferrous metals directly post shredding. The sensor can also be applied to improve the quality and throughput of SS.

2. Theory

A pulsed electromagnetic field is usually applied in non-destructive testing (NDT) for crack detection or the metallurgical property evaluation of metals (Cox, 1997). Compared to the single frequency, a pulsed technique allows multiple frequency operation at a single pulse. It is known that at low frequencies, low conductive metals such as SS experience deep penetrations of the eddy currents. These and other low conductive metals can better be distinguished from highly conductive ones by using a pulse excitation, which differs from the usual amplitude and phase analysis as described by harmonic techniques (Clauzon and Thollon, 1999).

2.1. Generation and detection of eddy currents in metals

For the generation of eddy currents in metals, an alternating magnetic flux is needed. Usually, a coil is used to create this changing magnetic flux. The flux is a function of the coil parameters and the primary excitation current. The oscillating nature of the flux induces (eddy) currents in the metal piece above the coil (Fig. 1). Current flows are orientated in a way so that the generated magnetic field opposes the field, which produces them (Lenz's law) (Bray and Roderic, 1997). The circular currents produce a secondary flux Φ_s. For most non-ferrous metals, Φ_s opposes the primary flux Φ_p. A receiver coil measures the resulting flux Φ_e, which is the difference between Φ_p and Φ_s.

The voltage measured with the receiver coil is given by Faraday's law:

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

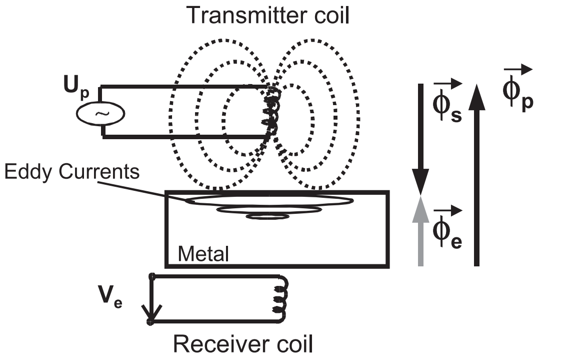

Fig. 1. Principle of generating and measurement of the eddy currents.

where N is the number of windings of the receiver coil.

Eq. (1) can be rearranged as a function of the magnetic field intensity:

$$V_e = N2\pi f \frac{\pi D^2}{4} \mu_0 \mu_{rel} H_e \tag{2}$$

where f=frequency (Hz), μ_0=magnetic permeability of air ($4\pi 10^{-7}$ H/m), μ_{rel}=relative magnetic permeability, D=diameter of the receiver coil and H_e=equilibrium magnetic field intensity (A/m).

For materials having different electrical and magnetic properties, V_e varies in response to H_e. At constant N, f, D and μ_0, H_e varies due to the variation of eddy currents into the specimen, which is directly related to differences in electrical conductivity (σ) (Charles, 1997).

The above statement was considered for harmonic signals, where a sinusoidal voltage is applied at the transmitter coil. When a pulsed system is considered, the difference compared to single frequency systems consists in the fact that the induced eddy currents are created by abrupt changes in the field due to suddenly interrupted excitation current at the transmitter coil. The change in the magnetic field is measured by changes in the voltage at the receiver coil. Although it is considered that for these systems signal analysis is difficult compared to the alternating field method, the pulsed systems showed improvements in metal differentiation when material size varies (Blitz, 1991).

2.2. Receiver coil parameters

The coil resistance (R) and reactance (X_L) are defined as the real and imaginary parts of the coil impedance (Z_s) when alternating current is applied (Fig. 2a). For different types of metals, a theoretical conductivity curve can be obtained by plotting the real versus the imaginary part of the receiver coil. This curve describes the distribution of the points obtained when R and X_L are plotted (Halmshaw, 1991). Depending on the alloy composition and particle size, different alloys or metals can be represented by the same point. In this simplification, differences in size and shape of the metal particles are ignored. Although it is easy to determine the position for each metal on the conductivity curve, smaller variations in the particle size and lift-off lead to abrupt movements of the impedance points. To obtain a uniform distribution of the metals on the conductivity curve, the operational frequency needs to be optimised. Previous literature described the influence of the operational frequency on scrap metals differentiation (Mesina et al., 2003).

When a pulsed method is applied, the spectrum over the frequencies is distributed over a large range and depends on pulse width. Compared to the method

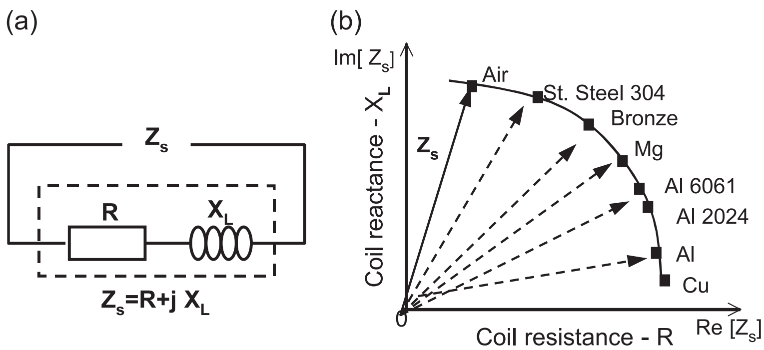

Fig. 2. (a) Imaginary and real part of the coil impedance; (b) conductivity curve for various metals.

where alternating currents are used, the pulsed method allows much higher depths of penetration of the eddy currents. Depth of penetrations of ten times higher than those obtained from the alternating fields are normally achieved (Bray and Roderic, 1997). This allows better signal interpretation and sensor optimisation for larger variations in particle size from the same class.

The depth of penetration of the eddy currents is defined as the distance at which the currents are 37% from their intensity at the metal surface. Previous literature described the variation for this parameter with the frequency and material composition for several metals (Mesina et al., 2003).

For the pulsed system, the signal measured at the receiver coil consists of a voltage, which changes when a metal is positioned above the receiver coil. The changes in the signal are caused due to electrical and magnetic properties of the test metal. Particle size and the distance between the receiver coil and the test metal have less influence on the signal compared to the alternating field method (Blitz, 1991).

3. Methods and materials

The developed PEMS prototype consists of a pulse generator, a transmitter coil and an array of receiver coils (Fig. 3). After amplification, the signal is analysed by an electronic unit that is able to detect SS from other non-ferrous particles based on differences in electrical and magnetic properties.

To analyse the signal variation from the receiver coil, 200 non-ferrous scrap particles were used. The material composition was chosen from SS, copper, cast aluminium, wrought aluminium, magnesium and brass having the size range of 20–60 mm (Fig. 4). For the experiments, austenitic and ferritic grades of SS were used. From electrical and magnetic point of view, there are fundamentally two classes of SS: (a) austenitic (300 class type), which is non-magnetic, and (b) ferritic (400 class type), which is usually soft magnetic. For this study, the difference between the two SS grades was made by applying a magnet. Those SS particles being attracted were classified as ferritic grades.

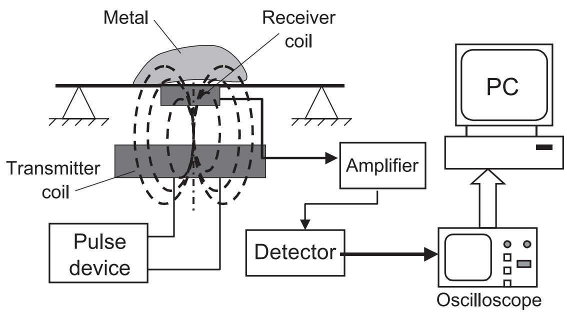

Fig. 3. Experimental set-up of the PEMS.

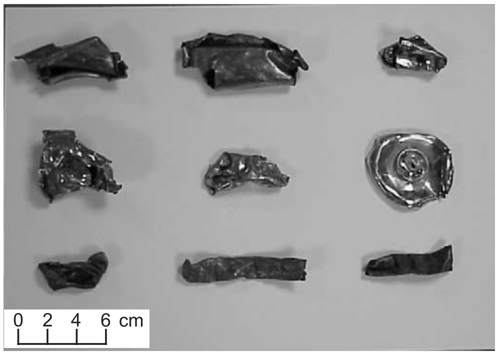

Fig. 4. Scrap particles from a shredder.

The first set of experiments was conducted in static mode, which means that a particle was manually placed above the receiver coil. For the second set of experiments, the particles were slid over the receiver coil, which was mounted under an inclined slide plate.

The transmitter coil has 40 windings and is of a rectangular shape (30×15 mm). The receiver coil has a diameter of 10 mm and 1500 windings. The pulse generator transmits pulses via the transmitter coil. The applied pulse rate is between 100 and 500 Hz and the pulse width is 100 μs. The pulse generator has a variable pulse length and repetition rate. The distance between the receiver and the transmitter coils was selected at approximately 70 mm. At this distance a maximum sensitivity for the differentiation of SS was obtained.

4. Experimental results and discussions

4.1. Pulse wave

The interaction between the metal particle and the magnetic field is measured with the receiver coil. In order to determine the metal composition, the changes in the signal are analysed and compared to the signal in absence of a particle. A sensor with a pulsed electromagnetic field was designed on laboratory scale for selective distinction of SS.

The pulse wave measured at the receiver coil presented in Fig. 5 was recorded in absence of test material. Two zones are defined: zone I, the upper part of the pulse, and zone II, the lower part.

The pulse shape changes when a particle passes over the receiver coil. Experiments with different metals showed that this variation depends on the following parameters: σ of the inspected material, the magnetic permeability (μ), particle size and the distance between the receiver coil and the metal particle—lift-off (x). The first two parameters are important to differentiate the metals from each other, while the last two are related to the geometry of the sample. The geometrical parameters affect also the sensor output. It is therefore necessary to study signal modifications in order to minimise or exclude the influence of geometrical factors on the differentiation process.

The depth (δ) at which the eddy currents are induced into the metal piece is closely linked to σ and f. Previous literature describes δ for different particles composition and explores how to apply δ to differentiate between non-ferrous metals by using electromagnetic sensors with an alternating magnetic field (Mesina et al., 2002a).

In Fig. 6, the variation of the pulse wave is given for cylindrical particles of 50 mm in diameter and

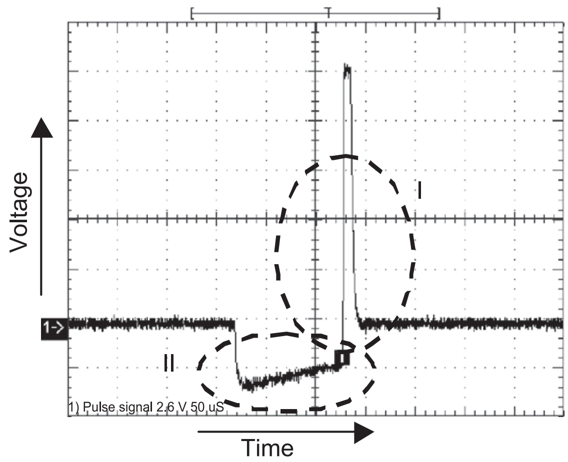

Fig. 5. The pulse wave measured at the receiver coil—zone I and zone II.

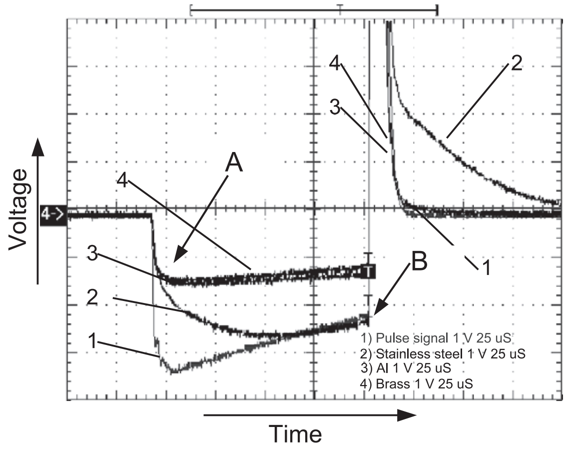

Fig. 6. The variation of the pulse wave for low, medium and high conductive metals: 1—pulse signal; 2—SS; 3—brass; 4—aluminium.

thickness of 5 mm. In zone I, the pulse wave changes significantly for SS compared to the other non-ferrous metals. The samples were chosen from low, medium and high conductive, e.g., SS, brass and aluminium. In zone II, SS shows exponential behaviour of the pulse compared to a less significant change in the output for the other metals.

Zone II changes according to Eq. (2), whereas H_e and therefore the signal varies little for SS at the point B (Fig. 6). The experiments conducted with different particle sizes showed that the variation of the pulse signal at point A depends solely on particle size. At point B, relevant information about the magnetic properties of the inspected particle is recorded.

Austenitic grades of SS have values of μ_{rel} slightly larger than 1, compared to other non-ferrous metals where μ_{rel} is usually 0.998. This causes a change in the orientation of Φ_e for SS (Fig. 1). For SS, Φ_e exceeds Φ_p due to the fact that Φ_s has the same direction as Φ_p. The higher μ_{rel}, the larger the secondary flux opposing the primary one. In this study, no investigation was conducted to differentiate between austenitic and ferritic grades using the PEMS, although SS was chosen from these two classes.

As described in literature, zone I represents the transient part of the pulse signal. Experiments conducted with different metals demonstrate that zone I is more affected by variations in σ and μ_{rel} and less by changes in the particle size or geometry.

The transient part of the signal also depends on the design of the transmitter coil, and it varies as a function of the time constant. The time constant is directly proportional coil resistance and inverse proportional to its inductance.

4.2. Static measurements

Similar to the experiments conducted with SS, brass and aluminium (Fig. 6), additional experiments were conducted to analyse only zone I of the pulse. For this set of experiments, the particles were placed by hand approximately in the middle of the receiver coil. The experiments conducted in static mode showed that by analysing only the transient zone sufficient information is recorded to distinguish SS from medium and high conductive metals, e.g., copper, cast aluminium, wrought aluminium, magnesium, zinc, brass and bronze (Fig. 7).

As discussed above, the changes in the pulse wave are not only dependent on σ and μ_{rel}, but also due to variations in particle size. The influence of x and particle size was further studied for static measurements. To measure variations in pulse wave due to metal–field interaction, a sampling time interval (y) was defined (Fig. 8a). y was chosen arbitrarily as a function of the pulse wave variation and the design parameters of the sensor.

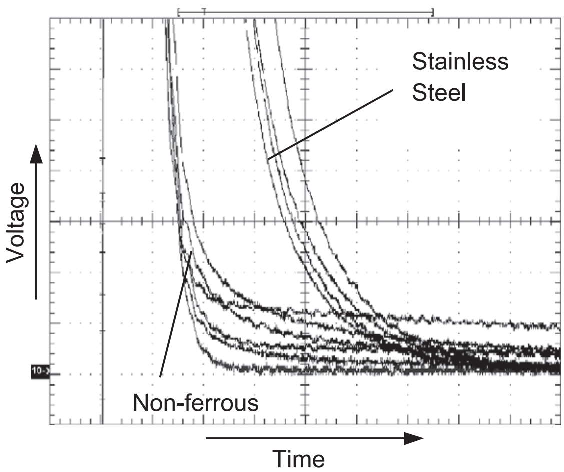

Fig. 7. The pulse wave attenuation in zone I for SS and other non-ferrous metals: aluminium alloys, magnesium, brass, bronze and copper.

Table 1 gives the results of U for different thicknesses of SS, aluminium and brass cylinders. All considered samples have a diameter of 50 mm. The voltage was recorded at y=75 μs, which was measured as shown in Fig. 8a. At this y, SS shows larger differences in U compared to aluminium and brass. As can be observed, even though the particle thickness increases, SS can be differentiated from aluminium and brass due to differences in U.

A shredder is applied for liberation of the different metals and size reduction. After shredding the particles have an irregular shape. As a result, x could vary differently even for particles from the same class. To study the influence of x to the pulse signal, experiments were carried out at different x up to 16 mm. For this set of experiments, only SS and aluminium samples were used. The chosen samples were of low and high conductivity. The particles were lifted gradually and variations of U at different x were recorded.

When a particle is lifted, the pulse signal gradually moves closer to the original pulse wave being recorded in absence of a particle. The experimental results showed that even for x=15 mm SS can be differentiated from aluminium.

Experiments conducted with SS and aluminium showed that for thicker particles the influence on x is less. The recorded data presented in Fig. 9 were measured at y=25 μs (Fig. 8a). The experiments were conducted with cylindrical particles of constant diameter (50 mm) having 5 and 10 mm thickness. The test particles were positioned above the receiver coil at different x ranging from 0 to 16 mm.

U decreases approximately in linear fashion when x increases (Fig. 9). For aluminium particles at x=16.5 mm, U decreases with approximately 70% compared to x=0, while for SS a decrease of only 40% was noticed. The signal variation with x is smaller for aluminium compared to SS. This means that with increasing distance x the differentiation between SS and aluminium improves.

4.3. Dynamic measurements—zone I

In practical applications, particles are moved on a conveyer belt with a speed up to 3 m/s. Experiments were conducted to investigate the influence of particle speed on sensor response. For these experiments, SS

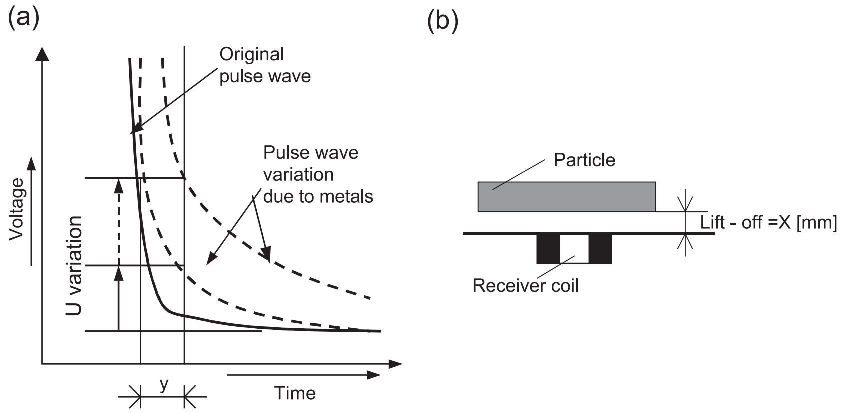

Fig. 8. (a) Schematic representation for y at variations in U; (b) lift-off distance (x).

and aluminium particles of a cylindrical shape of 50 mm diameter and thicknesses of 5 and 10 mm were used. During the experiments, U was measured for y=25 µs (Fig. 8a).

Fig. 10 shows the variation of U for the transient part of SS and aluminium when the particles move across the coil. The variable d is defined as the distance between the centre of the receiver coil and the projected centre of the inspected particle on the travelling path. When the centre of the particle has passed the centre of the receiver coil, d is negative.

During its movement across the receiver coil, a SS particle has a different influence on sensor response compared to aluminium. The maximum of U measured at y for SS is approximately 10 V, compared to 2.5 V for aluminium. At the same time, SS shows a maximum for U when the particle moves concentric towards the axis of the receiver coil. For aluminium, this maximum is found for $d=\pm 25$mm, which occurs when the edge of the particle is positioned above the centre of the receiver coil. This behaviour is called "edge effect". Experiments demonstrated that this effect is more significant when σ increases. Based on the results from the experiments conducted for different thicknesses and the variation of δ as described by Mesina et al. (2002b), it was observed that when the particle thickness approaches δ, a maximum edge effect occurs. This is especially important for the differentiation of SS from low conductive metals.

4.4. Dynamic measurements—zone II

The pulse wave of zone II also varies as a function of the particle position. Fig. 11a shows the voltage variation (V) of zone II for different d for aluminium and SS. V is measured at point B (Fig. 11b). The time interval between A and B is defined by the pulse width, which was chosen for this set-up at 100 µs. V increases when the test particle moves towards the receiver coil and it decreases after the particle edge

Table 1
Variation of U for SS, brass and aluminium at different thicknesses

Metal thickness (mm)	Voltage difference—U (mV)			
	Without metal	SS	Aluminium	Brass
5	0	1680	160	320
10	0	2160	250	400
15	0	2280	260	420

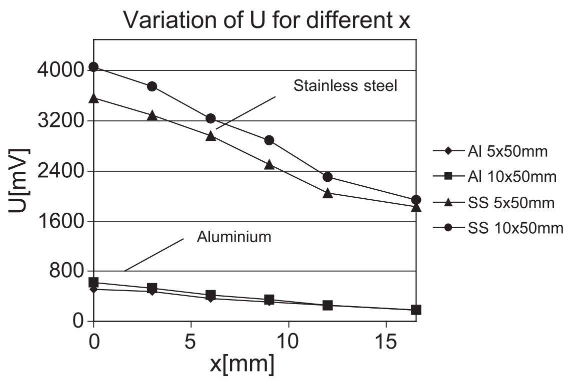

Fig. 9. Voltage variation for SS and aluminium at different particle thickness.

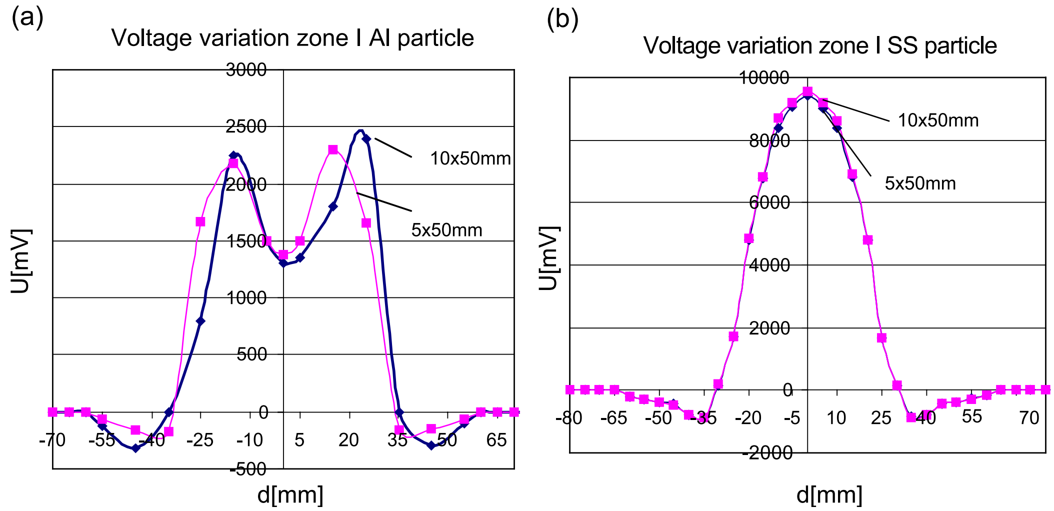

Fig. 10. Variation of U when the particle approaches the receiver coil: (a) aluminium; (b) SS.

has passed the receiver coil. When the particle is situated above the centre of the coil, a maximum of the voltage attenuation of zone II is observed. Comparing the signal variation recorded for SS and aluminium, SS shows a much smaller variation in V (Fig. 11b).

Experiments carried out with brass showed that V was measured almost half of the maximum variation of aluminium. With regard to the influence of the particle thickness and x it can be concluded that SS can be differentiated from other non-ferrous metals using only zone I of the pulse. It was observed that for thin SS particles (less than 3 mm in thickness) the variation of V for zone II is much smaller compared to zone I. As a result, zone I of the pulse provides more information for SS detection compared to zone II.

Particles having σ close to SS, e.g., tin and lead, were not considered in the experiments conducted with the PEMS. Although such metals record similar signal variations as SS due to low σ, no investigations were conducted to differentiate between these metals, as they are rare in typical non-magnetic post-shredder

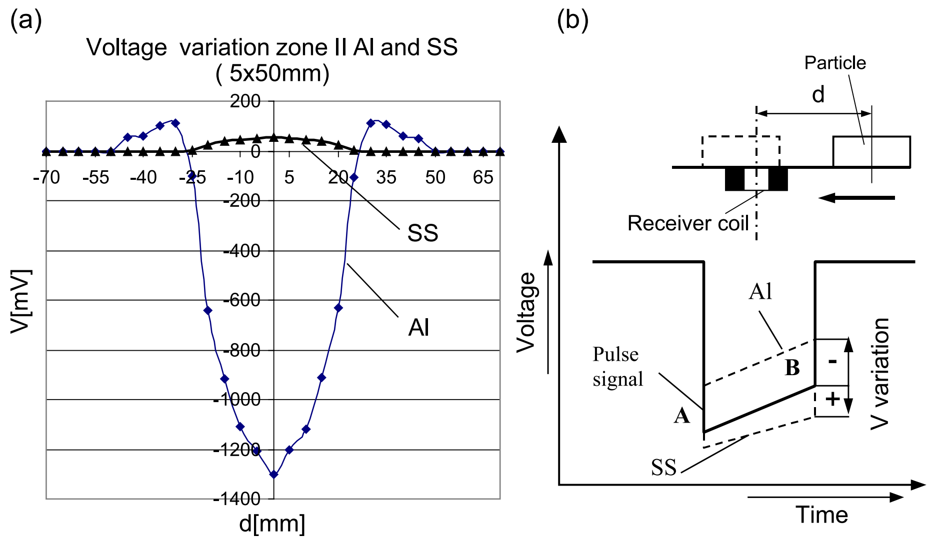

Fig. 11. (a) Voltage variation of zone II for aluminium and SS; (b) variation of V for zone II of the signal.

Table 2
Variation of U and V for different non-ferrous metals

Voltage variation zones I and II	Non-ferrous metals	
	SS	Medium and high conductive metals:, zinc, brass, magnesium, aluminium alloys and copper
Zone I Max (U) [mV]	7000 to 13 000	1700 to 4200
Zone II Max (V) [mV]	0 to 80	−1800 to −500

mixtures. For this application, further research on sensor design is necessary.

4.5. Detection of scrap SS

The experimental results discussed previously were considered for particles with defined size and geometry. In order to study the variation of the pulse signal for scrap particles, samples with different composition and irregular geometry were considered. The samples were selected from high, medium and low conductive. The maximum of U and V was recorded during the particle movement across the receiver coil for y=25 μs.

The results were obtained for 100 scrap particles with variations in particle size ranging from 20 to 60 mm (Table 2). SS shows larger variations in U compared to the other non-ferrous metals. As can be observed, for SS, V is positive, while for other metals, it shows a negative variation.

Although both zones of the signal show distinct differences for SS compared to the other metals, it was also observed that for scrap samples V records variations closer to the original signal when zone II is considered. This has the disadvantage that for smaller particle size or higher x, SS records weak signals and as a result SS might be not detected.

During particle movement, aluminium has a different trend for U in zone I compared to SS. This can be explained by the influence of the edge effect to the signal. It was also observed that this influence is more significant for highly conductive metals such as copper and aluminium alloys. For medium conductive metals, e.g., brass and zinc, the edge effect is less significant.

4.6. PEMS prototype for SS separation

Based on the interpretation of the results obtained for dynamic measurements, an experimental set-up for the identification and separation of scrap SS was constructed using the PEMS sensor (Fig. 12). The system analyses only zone I from the signal. An array of four receiver coils was mounted below a conveyer belt, and connected to a processing unit for signal interpretation. The data was sent to a computer using a Keithley KPCI-PIO24 data acquisition card. The electronic unit evaluates the signal and when a SS particle is detected, the signal is further transmitted to the digitisation unit.

The particles being detected by the PEMS are ejected from the stream using an actuator, which is activated by the processing unit. In practice, conveyer blowbar systems could be use. For the present tests, new design of an actuator was applied. Its main

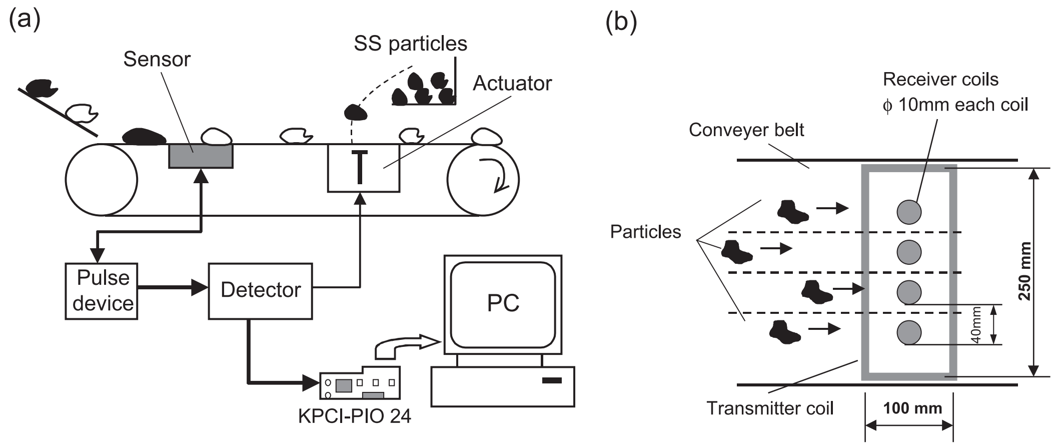

Fig. 12. (a) Experimental set-up for SS separation using the PEMS; (b) sensor geometry.

objective was multi-fraction actuation. The ejection mechanism consists of pneumatic hammers installed under the conveyer belt. These are controlled by electronics being part of the PEMS system. The design and working principle for the actuators was described by de Jong et al. (2001).

A mixture of non-ferrous scrap particles containing austenitic and ferritic SS in a proportion of 10 to 3 was tested. In practice, it is relevant to separate austenitic SS from the non-ferrous metals mixture, because most ferritic grades can be removed by low intensity magnetic separation. The experiments were conducted with 200 particles and the belt velocity was approximately 0.5 m/s.

The computed grade and recovery for SS are presented in Fig. 13. As can be observed, SS is detected and removed with a purity of 100% and an average recovery of 94.5%. To study the influence of particle orientation on the sensor response, repetitive experiments were conducted using the same test particles. The results are shown in Table 3.

The sensor was designed to detect particles with a minimum area cover of about twice the receiver coil diameter. Even though the test particles are placed at an x up to 10 mm from the top of the receiver coil, the SS particles can be detected by the electronic unit. By adjusting repetition rate and pulse width, higher velocities of up to 2.5 m/s can be applied. The prototype system was designed on laboratory scale and the tests were performed at lower velocities.

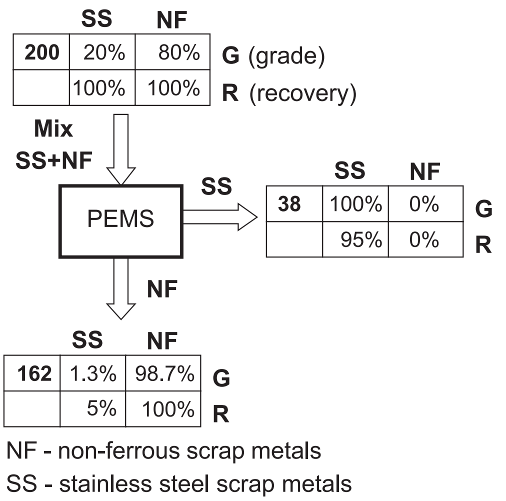

Fig. 13. Flow sheet of grade and recovery for PEMS-20/80 SS/NF.

Table 3
Experimental results of scrap SS separation with the PEMS

No. experiments	Grade	Recovery
1	100	92.5
2	100	95
3	100	97.5
4	100	97.5
5	100	95
6	100	90
7	100	95
8	100	92.5
9	100	95
10	100	95
Average	100	94.5

The proposed PEMS prototype uses four receiver coils for particle identification at a belt width of 30 cm (Fig. 12b). An increase in the number of the receiver coils leads to larger output capacity and sensitivity of the sensor. For a mixture of SS and heavy non-ferrous metals, it is estimated that for a system with a belt width of 1 m and 2.5 m/s particle velocity, a throughput of 10–15 t/h can be obtained.

The PEMS is an on-line sensor system that inspects the stream particle by particle. Based on the information being processed with an electronic unit, the system automatically ejects SS from mixed scrap. The proposed system can be also used for quality monitoring of the input feed as well as for data collection and process control. At the same time, management of the entire system including shipments of the product can be better controlled and optimised.

5. Conclusions

The PEMS system automatically identifies and separates scrap stainless steel from other non-ferrous metals based on electrical and magnetic properties. The experimental results show that 95% of the stainless steel can be recovered with a grade of almost 100%. A practical application of the system comprises the removal of scrap stainless steel from other non-ferrous metals in the non-magnetic metal fraction from industrial shredders.

Due to the fact that the magnetic field interacts only with the metal particle, the PEMS is insensitive to dust or other impurities covering the particle surface. The system can operate post shredding and no feed preparation or pre-processing steps are required. Furthermore, the PEMS system is not restricted to any safety regulations, it is easy to use and mechanically robust.

Symbol list

d	distance from the receiver coil to the particle [mm]
D	receiver coil diameter [mm]
f	field frequency [Hz]
K	constant
H_e	equilibrium magnetic field intensity [A/m]
N	receiver coil windings number
R	coil resistance [Ω]
U	voltage variation zone I pulse [V]
V	voltage variation zone II pulse [V]
V_e	voltage at the receiver coil [V]
x	lift-off [mm]
X_L	coil reactance [Ω]
y	time sampling [μs]
Z_s	receiver coil impedance [Ω]
δ	depth of penetration of Eddy Currents [mm]
Φ_e	equilibrium flux [Wb]
Φ_p	primary flux [Wb]
Φ_s	secondary flux [Wb]
μ_0	air magnetic permeability [$4\pi 10^{-7}$ H/m]
μ_r	material magnetic permeability [H/m]
σ	electrical conductivity [S]

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