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Eddy current evaluation of recovered conductive waste purity

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ABSTRACT

The main goal of this paper is to present a new approach to evaluate the recovered conductive granular waste purity. For this purpose, the eddy current approach which is commonly applied in nondestructive evaluation has been used. The experimental tests consist of several samples composed of copper particles mixed with sand inserted in a cylindrical container with solenoidal coil. The impedance of the coil is measured, using precision LRC-meter, for several frequencies per sample and used according to the Experiment Design Methodology (EDM) to determinate the relationship between input and output of experiments, to have a quadratic model that will be used for inversion. The input and output are successively impedance and percentage of copper particles contained in the container. The results show the capability of the proposed approach to evaluate the conductive recovered waste purity.

1. Introduction

Due to the technologic evolution and the widespread use of electronic devices the amount of electric and electronic equipment wastes (WEEE) has been increased during the last decades, in a way never seen before which gave waste management a great importance on the environmental, economic and social level (Torretta et al., 2013; Miloudi et al., 2015). The continuous accumulation of this wastes leads to the pollution of the environment (Asokan et al., 2007). For this reason, Recycling becomes a very important operation. Moreover, the recycling of WEEE is cheaper than the extraction of raw materials (Dalmijn and De Jong, 2007).

Wastes sorting are an essential step in the recycling process; it consists of separating and recovering the wastes according to their nature. The main two steps of recycling WEEE are sorting and processing. In the sorting step, wastes go through several stages, primarily the shredding and separation (Menad et al., 2012; Fabrizi et al., 2003). At the end of the sorting procedure, the materials are in granular form. But the presence of impurities such as insulating particles mixed with conductors reduces the quality of the recycled products.

In the field of electrostatic separation of conductive and non-conductive materials the process is affected by various parameters (voltage levels, material flow, speed of drum, granules size and shape, etc.), which are reflected to the middling product (Fig. 1) and therefore on the efficiency of separation (Lai et al., 2015; Dascalescu et al., 2014). That is why there is a great need to know the percentage of impurities in the given volume of recycled conducting materials (Jujun et al., 2014; Zeghloul et al., 2016).

Eddy current (EC) evaluation is a technique used in electromagnetic and geometric characterization of conducting materials.

In this work, the EC technique has been implemented to evaluate the percentage of purities after separation of conductive waste. The recovered waste is introduced in a cylindrical container immersed in a solenoidal coil.

To demonstrate the capability of eddy current technique to evaluate the purity of conductive waste after separation, several samples of recovered conductive waste are formed using pure copper mixed with insulating particles, the samples occupy the same volume but they are different in the proportions of copper and insulator that it formed.

The Experiment Design Methodology (EDM) is then used to get the mathematical relation (prediction model) between the parameters of eddy current evaluation and the purity of the recovered conductive waste.

The experimental setup (Fig. 1) is performed with a solenoidal coil surrounding a cylindrical container that is dedicated to the proposed tests. This container is filled each time with one of the samples then, the impedance of the probe is measured using a precision LCR-meter for several frequencies. The used platform of the EDM is MODDE 5.0 software (Dascalescu et al., 2004; Eriksson et al., 2000). The inputs parameters of EDM are percentage and length of the conductive particles, and the output one is electrical impedance of the coil. To get the percentage of conductive particles

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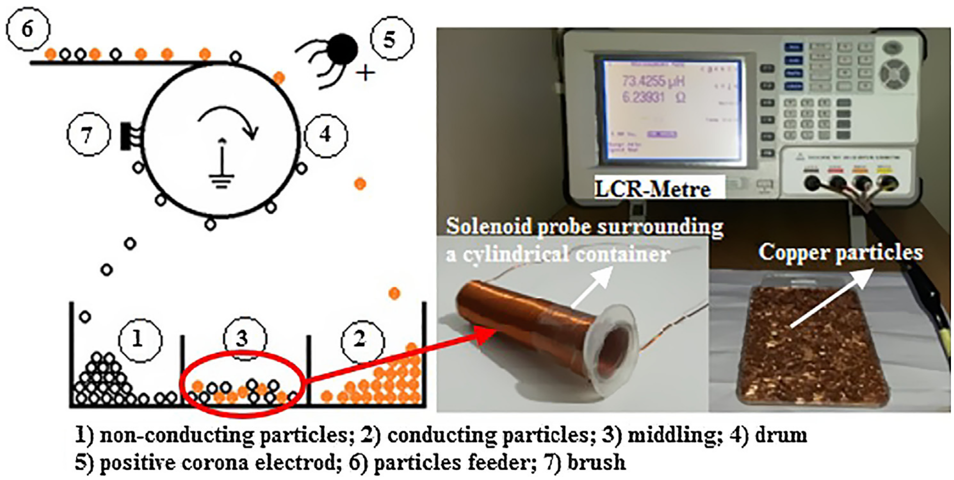

Fig. 1. Experimental setup.

contained in the recovered waste, the obtained mathematical model must be inversed.

2. Experiment setup

In our experimental setup the recovered waste samples are created by mixing the conductive and insulating particles. The conductive particles are from copper wire. Fine sand is used as insulating particles. Each sample is inserted in a PVC cylindrical container with a known volume.

The impedance of the coil, surrounding the cylindrical container, is measured using a precision LCR meter.

To obtain the purity percentage of recovered waste samples, the weight of copper is taken by using a precision balance.

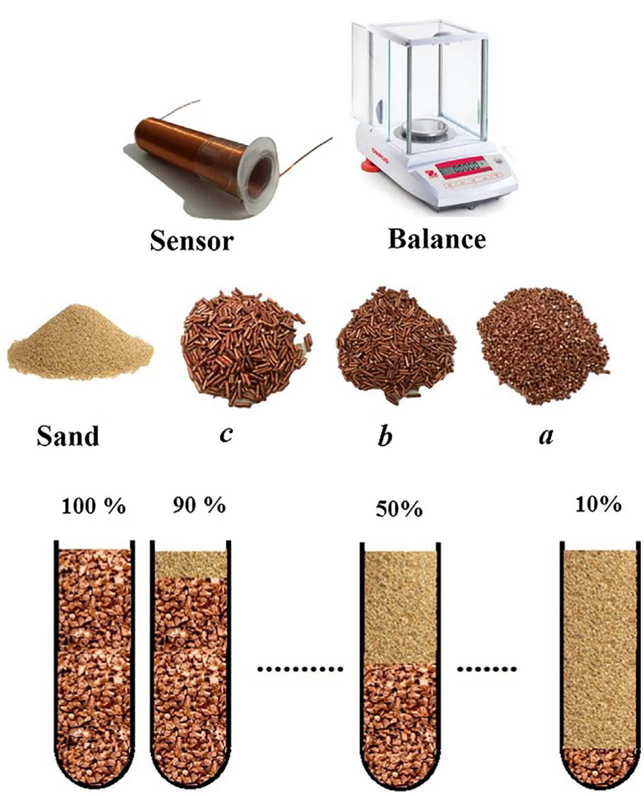

Fig. 2. Materials and equipment used to prepare samples.

Fig. 2 shows all materials and equipment used in the experimental setup.

Table 1 gives the geometric parameters of the problem.

3. Sample preparation steps

Samples preparation is a crucial step in the characterization process, in which all samples have the same volume.

To obtain the cylindrical conductive particles, a copper wire with a circular section is manually cut into three groups (a, b and c) whose lengths are successively 1 mm, 3 mm and 5 mm.

For the first sample, the entire volume of the container is filled with copper particles of identical length. This sample represents the case of perfect purity of recovered waste with 100% of copper and 0% of sand (insulator).

The other samples with different percentages of copper are obtained by extracting, step by step, an amount of copper (multiple of 10%), replaced by another amount of sand in order to maintain the same volume of the samples. The percentage of copper (Co) in the sample is computed as follow:

$$\text{Sample}_{\text{Co\%}} = \frac{\text{Weight of Co in sample}}{\text{Weight of Co in first sample}} \times 100 \tag{1}$$

The weight of copper particles is obtained using a precision balance.

Finally, the impedance of coil is measured according to the frequency (4–100 kHz) for all samples by filling the container each time with a sample (Fig. 3).

Table 1
Dimensions of Experimental setup constituents.

Dimensions	Values
Cylindrical container	
Inner diameter (mm)	13
Height (mm)	6.1
Solenoid coil	
Height (mm)	5.84
Inner diameter (mm)	14.5
Number of turns	101
Copper cylindrical particles	
Average particle lengths (mm) groups A, B, C	1, 3, 5
Diameter (mm)	0.5

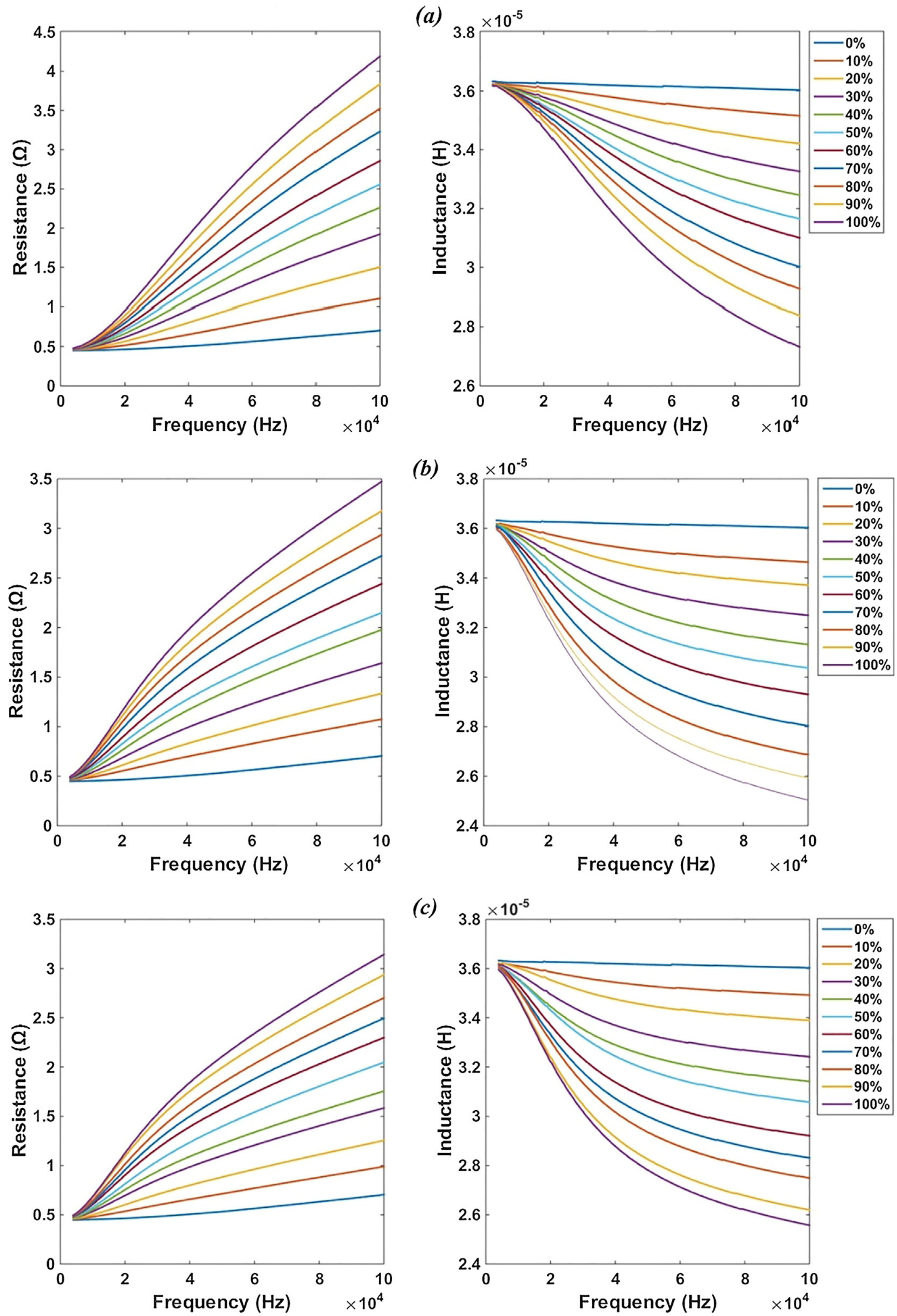

Fig. 3. Resistance and inductance of solenoidal coil as function of frequency of different lengths of copper particles (a) Length of particle equal to 1 mm; (b) Length of particle equal to 3 mm; (c) Length of particle equal to 5 mm.

4. Design of experiments methodology

On the basis of statistical theories, Experiment Design Methodology (EDM) provide an effective way to specify the number of experiments to be realized, to study several factors that can vary simultaneously, to evaluate the significance of the effects of each factor and to minimize dispersion that affects measurements (Eriksson et al., 2000).

In our case, the dependence between the input and output parameters of the EDM is shown in (Fig. 6). The input parameters

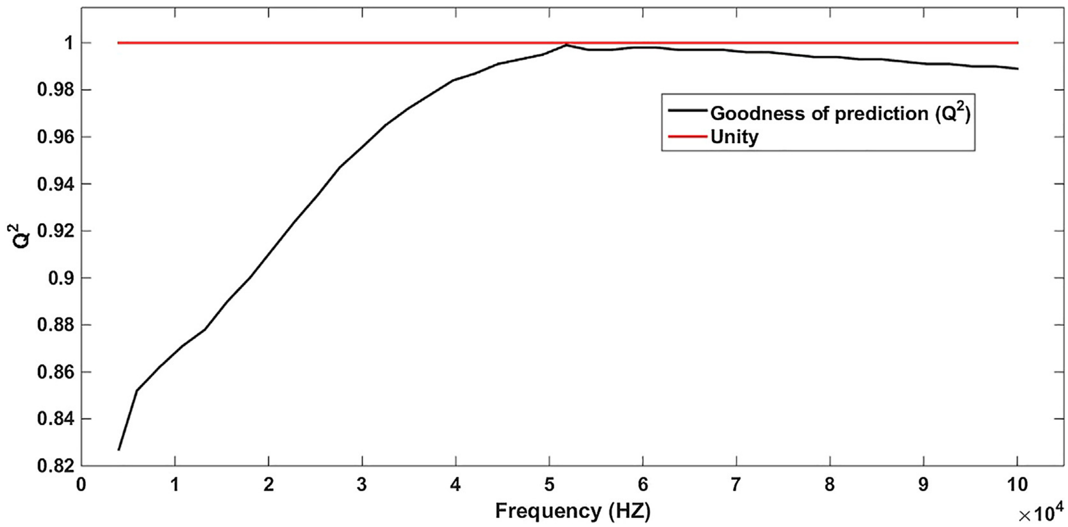

Fig. 4. Evolution of goodness of prediction index as function of frequency.

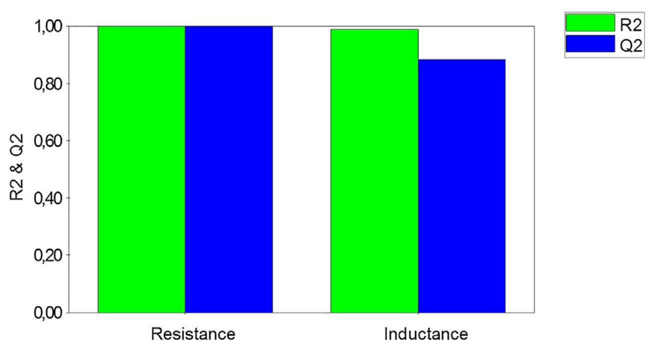

Fig. 5. MODDE 5.0 - summary of inductance and resistance fit.

are the percentage (p_e) and the length (L_e) of the particles of the recovered conductive waste and the output parameters are the resistance or the inductance of the solenoid coil.for this study the system modeling is done according to composite center faces design (CCF) to ensure a quadratic dependence between the factors and their response as follows (Dascalescu et al., 2004):

$$y = a_0 + \sum a_i x_i^* + \sum a_{ij} x_i^* x_j^* + \sum a_{ii} x_i^{*^2} \quad (2)$$

The inputs (factors) are expressed by the reduced central values x_i^* for the n variable x_i of the process with (Richard et al., 2017):

$$x_i^* = (x_i - x_{i0})/\Delta x_i \quad (3)$$

and

$$x_{i0} = (x_{iMax} + x_{iMin})/2; \;\; \Delta x_i = (x_{iMax} - x_{iMin})/2 \quad (4)$$

The values of the predictive model coefficients (a_0, a_i, a_{ij}, a_{ii}) are extracted using MODDE 5.0 software.

The total number of experiments (N) to be achieved for (k) factors is given as follows:

$$N = K^2 + 2K + 3 \quad (5)$$

The main two factors to be controlled are the length (L_e) and the quantity (in percentage) (p_e) of copper particles inside the container in order to show their effects on the components of the solenoid impedance which is excited by a precise frequency.

Two statistical index R^2 (goodness of fit) and Q^2 (goodness of prediction) are calculated and presented to evaluate the quality of the mathematic model (Dascalescu et al., 2004).

Generally, a perfect model present R^2 and Q^2 equal to unity (Richard et al., 2017).

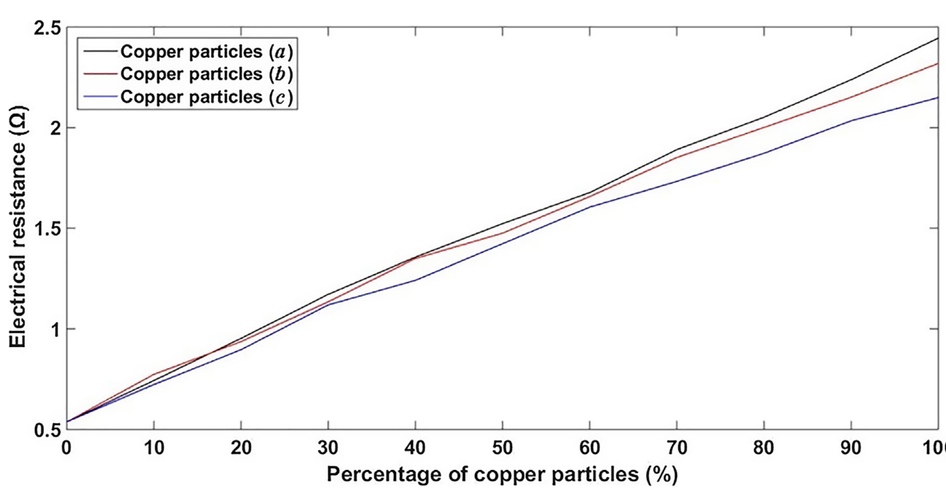

Fig. 6. Solenoid resistance as a function of percentage for different length of copper particles.

The first step was allocated for the selection of the optimal frequency, in which several mathematical models were obtained using MODDE 5.0 software, so that in each case the excitation frequency of the solenoid was changed. And according to the evolution of the goodness of prediction Q^2 (Fig. 4) the optimum frequency has been selected.

In the second step the resistance (R) was chosen instead of the inductance (L) to be the response of the system because the mathematical model based on the resistance as a response has a high predictive capacity (Fig. 5).

Fig. 6 shows the linear relationship between the measured resistance (R) and the percentage (Pe) of copper particles inside the container, while the value of the resistance is direct proportional to the amount (percentage) of copper particles inside the container and is inversely proportional to the length of copper particles, because the container filling rate increases when the length of copper particles decreases.

After selection of the working frequency (51,800 Hz) and the introduction of the appropriate experimental data of the system Table 2, MODDE 5.0 has established the general CCF model using MLR (multiple linear regression) algorithm (Dascalescu et al., 2004).

$$R = a_{11}Pe^{*^2} + a_{22}Le^{*^2} + a_{12}Pe^{*}\ Le^{*} + a_1Pe^{*} + a_2Le^{*} + a_0 \quad (6)$$

Table 2
Results of the composite center faces (CCF) experimental design.

Run no.	Pe (%)	Le (mm)	R (Ω)	L (H)
1	5	1	0.636	3.59e−005
2	100	1	2.44565	3.07e−005
3	5	5	0.638	3.56e−005
4	100	5	2.15015	2.77e−005
5	5	3	0.64	3.57e−005
6	100	3	2.31998	2.75e−005
7	52.5	1	1.58	3.328e−005
8	52.5	5	1.42	3.184e−005
9	52.5	3	1.521	3.161e−005
10	52.5	3	1.522	3.161e−005
11	52.5	3	1.527	3.164e−005

Table 3
Coefficient values of the quadratic model.

Coefficient	Value
a_0	+1.5210600
a_1	+0.8336300
a_2	−0.0755834
a_{11}	−0.0376624
a_{22}	−0.0176529
a_{12}	−0.0743751

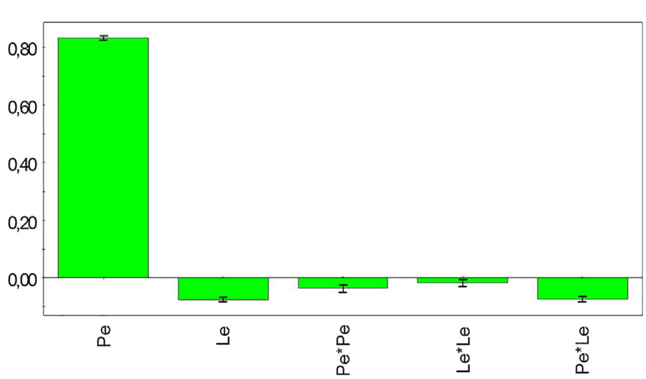

Fig. 7. MODDE 5.0 - effects of model coefficients on electrical resistance.

This model is only valid for copper particles that range from 1 to 5 mm of length.

The coefficients of the controlled factors and their interactions that were provided by MODDE 5.0 software are given in Table 3:

The effects of the factors (Pe, Le) are important for the system, but the most significant factor is the percentage (pe), while the influence of the interaction between the two factors is lower (Fig. 7).

Table 4
The resistances correspond to different lengths and percentages of copper particles.

Pe (%)	R_a (Ω)	R_b (Ω)	R_c (Ω)
0	0.53779	0.53779	0.53779
5	0.63600	0.64000	0.63800
10	0.74400	0.77500	0.72300
15	0.81800	0.85500	0.84500
20	0.95300	0.93700	0.89700
25	1.05324	1.05357	1.05831
30	1.17225	1.13536	1.11956
35	1.25889	1.23942	1.20320
40	1.35675	1.34952	1.24178
45	1.42990	1.41349	1.33220
50	1.52318	1.47587	1.42332
55	1.62640	1.59312	1.53605
60	1.67766	1.65738	1.60506
65	1.77935	1.73817	1.64961
70	1.89139	1.85216	1.73331
75	1.99134	1.92694	1.81080
80	2.05228	2.00143	1.87316
85	2.14971	2.06470	1.94808
90	2.23879	2.15178	2.03455
95	2.32549	2.22647	2.08867
99	2.42063	2.27682	2.14699
100	2.45600	2.31998	2.15015

Table 5
Coefficients values of the equations corresponding of each length (a, b, c).

Le^*	α	β	γ
−1	−0.03766	0.908	1.57899
0	−0.03766	0.83363	1.52106
1	−0.03766	0.75925	1.42782

Table 6
Roots obtained from solving all equations.

Percentages (%)	Roots		
	r_a	r_b	r_c
5	−0.99727733	−1.01074119	−0.99149713
10	−0.88695729	−0.86142809	−0.88909768
15	−0.81082149	−0.7720577	−0.74043085
20	−0.67075162	−0.67974742	−0.67644011
25	−0.56574147	−0.54725772	−0.47546543
30	−0.43992224	−0.45338829	−0.39814492
35	−0.34752222	−0.33284263	−0.29162882
40	−0.24232130	−0.20389649	−0.2421265
45	−0.16309238	−0.12829444	−0.12516699
50	−0.06130905	−0.05407659	−0.00592999
55	0.05232638	0.08678147	0.14356517
60	0.10916049	0.16475208	0.23620202
65	0.22271643	0.26357801	0.29647043
70	0.34910552	0.40457346	0.41071785
75	0.46301923	0.49809130	0.51770564
80	0.53302564	0.59207649	0.60468119
85	0.64584329	0.67257265	0.71024220
90	0.74997742	0.78439184	0.83357502
95	0.85225887	0.88127899	0.91161091
99	0.96558272	0.94711593	0.99645325
100	1.00800934	1.00389417	1.00107298

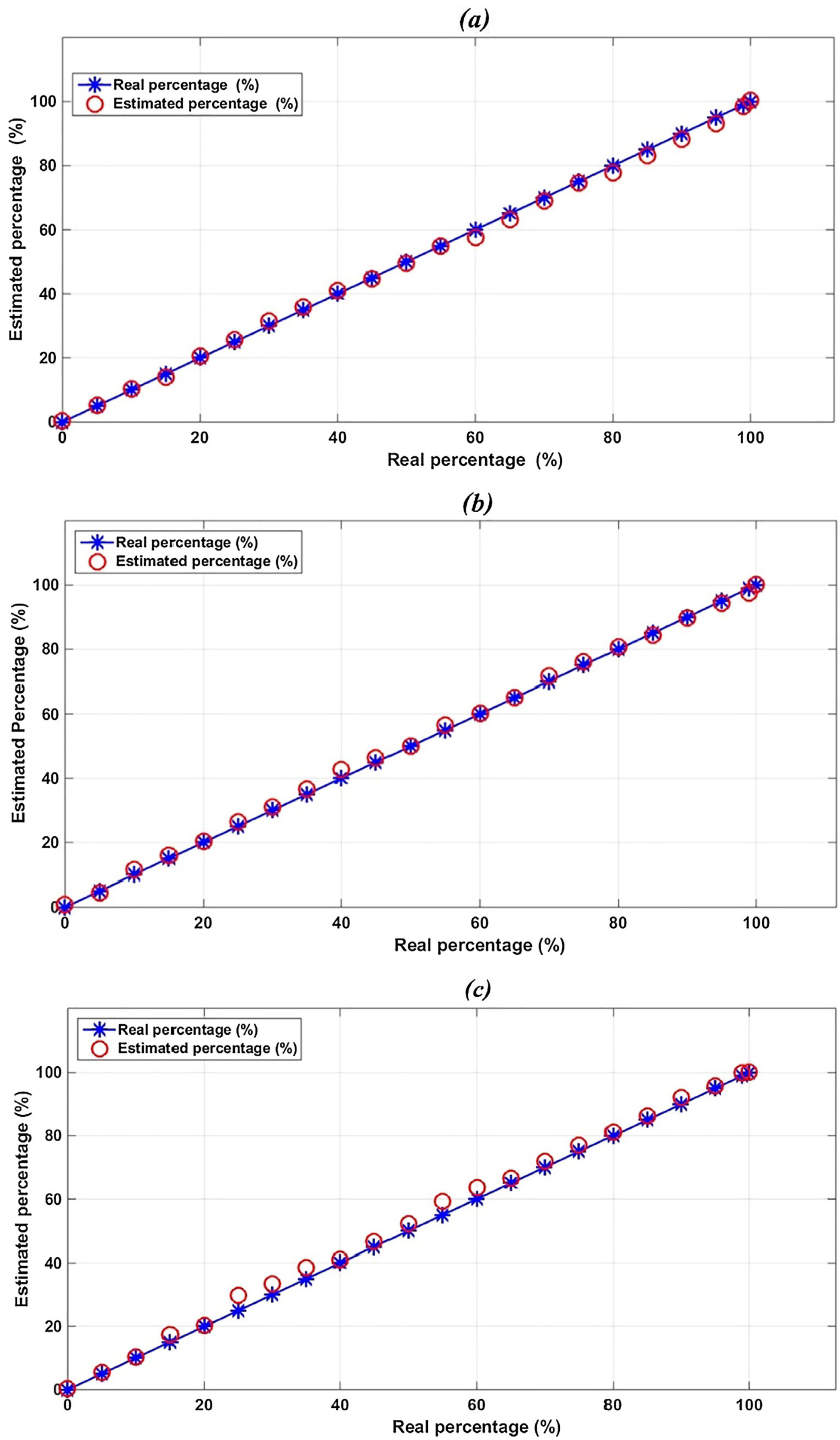

Fig. 8. Evaluation of the purity of copper particles with different lengths (a, b, c).

5. Inversion method

As mentioned earlier, the purpose of this paper is to predict the percentage of copper particles inside the container from the solenoid resistance, which requires solving Eq. (6), assuming the knowledge of the electrical resistance (R) and the length of copper particles (Le).

Table 4 show the measured electrical resistance (R) of three different groups of copper particles whose length varies from 1, 3 and 5 mm with several percentages per group.

If these lengths are centered normalized and replaced in Eq. (6), they will result in three different equations in form:

$$(\alpha)Pe^{*^2} + (\beta)Pe^{*} + (\gamma - R) = 0 \quad (7)$$

The coefficients (α, β, γ) of the three equations corresponding to the lengths (a, b, c) expressed in centered normalized values (Le^*) are presented in Table 5.

For each equation, (R) should be replaced by its appropriate value given in Table 4, so get an equation for each percentage per group.

In this way, the roots of each equation are calculated and presented in Table 6.

All these operations are handled by MATLAB software. r_a, r_b, r_c: are the roots of each equation that represent the percentages ($pe^{*)}$ in centered normalized value.

Since the centered normalized values are limited between 1 and -1, the other roots were rejected.

From Eq. (3) the estimated percentage can be expressed as:

$$Pe_i = (Pe^* \times \Delta Pe_i) + Pe_{i0} \quad (8)$$

$$P_{i0} = (100 + 5)/2; \ \Delta Pe_i = (100 - 5)/2 \quad (9)$$

the extracted values of the estimated percentage are plotted compared to the real ones (Fig. 8).

The conformity of the estimated results with the real results demonstrated the accuracy of the mathematical model and its high predictive ability, regard less the length of copper particles used.

6. Conclusion

In order to improve the separation strategy, the eddy current technique associated with the Experiment Design Methodology (EDM) was applied to evaluate the percentage of copper particles mixed with sand and submitted in a cylindrical container this achievement represents an effective means for the continuous monitoring of the recovered wastes compartments.

The linear dependence between the amount (percentage) of copper particles inside the container and the electrical resistance of the solenoid was the main catalyst for modeling, while the inverse model is the one responsible for predicting the percentage of copper particles inside the container from the measured resistance.

The results show the ability of the process to ensure the purity of the recovered conductive and non conductive materials.

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