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DETERMINATION OF THE ANODIC DISSOLUTION DEPENDENCIES OF A MULTICOMPONENT ALLOY AS THE PRODUCT OF PRINTED CIRCUIT BOARD PROCESSING IN ELECTROLYTES BASED ON SULPHURIC AND METHANESULFONIC ACID

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The object of the study is the process of anodic dissolution of a multicomponent metallic alloy obtained from the recycling of printed circuit boards (PCBs). Such feedstock consists mainly of copper, tin, nickel, lead, and iron, which complicates its subsequent hydrometallurgical processing and requires the selection of an efficient electrolyte for the initial dissolution stage. A key challenge of the first processing stage is converting alloy components into a soluble form, which can be intensified by selecting an appropriate electrolyte composition and current density. To enhance the rate of electrochemical dissolution, a methanesulfonic acid electrolyte was used for this alloy composition. The results were compared with those obtained in a sulfuric acid electrolyte. Electrochemical characteristics were determined using cyclic voltammetry at different potential scan rates. Qualitative and quantitative evaluation of the anodic process was performed by analyzing cyclic voltammograms and the specific charge consumed during dissolution. The surface composition of the alloy before and after dissolution was determined by X-ray fluorescence analysis, while the composition of the electrolyte after electrolysis was used to evaluate the relative amounts of metals transferred into solution.

It was shown that anodic dissolution of the alloy proceeds more intensively in the methanesulfonic acid electrolyte than in the sulfuric acid medium. The specific charge associated with the anodic process was found to be 2–3 times higher in the methanesulfonic acid solution. It was established that during dissolution in a 1 M methanesulfonic acid electrolyte, copper and nickel dissolve mainly, whereas tin and lead accumulate on the surface as low-soluble products. After electrolysis, the alloy surface became enriched in tin and nickel, while the surface deposit contained elevated amounts of tin and lead. These findings indicate the selective nature of the process and the possibility of partial component separation as early as the first stage of electrochemical processing. The results obtained may be applied to the development of recycling technologies for multicomponent alloys, generally consisting of copper, nickel, tin, and lead

Keywords: anodic dissolution, methanesulfonic acid, sulfuric acid, printed circuit boards

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1. Introduction

The independence of Ukraine necessarily includes resource and technological independence. This means that self-sufficiency in critical materials and technologies should be one of the highest priorities of state policy. This is especially important for materials, which deposits are absent in Ukraine.

Recycling of printed circuit boards (PCBs) can be a source of valuable and critical metals. This is because a wide range of metals and non-metallic materials are used in the produc-

tion of PCBs, including copper, tin, nickel, silver, lead, gold, palladium, and other metals [1, 2].

According to the Global E-waste Monitor 2024, the worldwide generation of electronic waste reached approximately 62 million tons in 2022 and is expected to increase to 82 million tons annually by 2030 [3].

According to [4, 5], PCBs account for 3–7% of electronic waste, corresponding to about 1.86 million tons in 2022 at the lower estimate of 3%. This represents enormous amounts of materials that can be recovered, separated, and reused.

In [6], it was shown that the total amount of electronic waste in Ukraine may exceed 1 million tons per year. Accordingly, even the minimum amount of PCBs may reach 30000 tons per year or more. At such large volumes, PCBs can become an important secondary source of strategic metals and non-metallic materials. Therefore, studies aimed at developing efficient methods for recovering valuable materials from PCBs are relevant.

2. Literature review and problem statement

Chemical or electrochemical dissolution is often the first step in the processing of multicomponent alloys because it does not require high temperatures and is much less dependent on the mechanical and thermal properties of materials [7].

Thermal processing of PCBs produces multicomponent alloys containing mainly the following elements: Cu, Sn, Ni, Pb, Fe, Al, Zn, Ag, and Au [8]. Among these elements, Cu and Sn usually predominate, as they form the basis of PCBs and are used to connect functional components such as resistors, capacitors, and microchips.

Leaching of copper from crushed PCB particles was carried out in an H_2SO_4 solution using H_2O_2 as an oxidizing agent at room temperature [9]. The authors identified a combination of optimal conditions, including particle size and solution composition. Nevertheless, such a solution is aggressive, may form aerosols, is not environmentally friendly enough, and does not address the recovery of other components. Another significant disadvantage is the lower dissolution rate compared to electrochemical methods.

In [10], the behavior of a recycled Cu anode with a non-standard impurity content was studied in an H_2SO_4 solution. The anodes were produced by casting wastes generated during Cu refining and contained Ni (<10%), Sn, and Pb (1–3%). It was shown that passivation of the recycled anode during dissolution did not occur. However, the use of an aggressive and environmentally unfavorable electrolyte limits the application of this method.

Study [11] investigated the behavior of Cu anodes containing oxygen, silver, and selenium impurities during electrorefining in H_2SO_4 at 65°C. Voltammetric, chronopotentiometric, and impedance methods were used. The authors showed that anode passivation increased when impurities were added in the following order: Cu → Cu-O → Cu-Ag → Cu-Se → Cu-Ag-Se. X-ray diffraction results demonstrated that the anode surfaces in the passive region were covered by copper powder, silver, and selenides. It can be noted that under these conditions the sulfuric acid electrolyte did not demonstrate selectivity and, due to the presence of sulfuric acid, remained aggressive and environmentally unfavorable.

In [12], devoted to the influence of additives (thiourea, glue, and chloride ions) on improving Cu deposits at the cathode, their role in anode passivation during copper electrorefining was shown. The electrolyte at 65°C contained 40 g/L Cu^{2+} and 160 g/L H_2SO_4. It was found that increasing the Cl- concentration increased the passivation time, whereas thiourea concentrations above 2 ppm reduced the passivation time. However, the use of sulfur-containing solutions still leaves open the question of environmentally safe treatment of the spent electrolyte.

In [13], the electrochemical dissolution of Au and Cu from their alloys in cyanide-containing solutions was studied using a rotating disk electrode. It was shown that alloy dissolution was controlled partly by the electrochemical reaction and largely by mass transfer. Nevertheless, the high toxicity and relatively low conductivity of such electrolytes significantly limit their industrial application.

Work [14] was devoted to determining the conditions of electrochemical copper dissolution in dilute hydroxylamine solutions for electrochemical mechanical planarization of copper. The disadvantage of the proposed electrolyte is the low conductivity of the solutions, which increases the specific energy consumption, and the lower dissolution rate. Therefore, it can be applied only for this specific treatment process.

The anodic behavior of Sn in sulfuric acid solutions was also studied [15]. The researchers observed partial passivation of tin in 4.5–8 M H_2SO_4. It was also found that tin dissolved both in the active and partially passive potential regions in the form of divalent tin. Non-electrochemical methods showed that the film mainly consisted of tin oxide, SnO, predominantly in an amorphous form.

Dissolution of Sn in dilute citric acid solutions was demonstrated in [16]. However, the use of such electrolytes in industrial processes may be limited by their relatively low conductivity as well as by the complexation behavior and solubility of some metal citrate compounds.

For the production of stannate, dissolution of Sn in an oxidizing alkaline NaOH-H_2O_2 medium enhanced by ultrasound to suppress passivation was proposed in [17]. However, when such an electrolyte is used, a limitation is the absence of amphoteric behavior of other metals present in the alloy. This may lead to the formation and accumulation of insoluble hydroxides.

A similar limitation for industrial application exists for an alkaline electrolyte containing iodates [18].

The behavior of Sn in tartaric acid solutions at concentrations of 0.1–1.5 M and pH ≈ 1.0 at 25°C was also investigated [19]. The authors showed that oxidation in tartaric acid solutions exhibited active-passive transition behavior, while Sn dissolved in the active potential region as Sn(II) species, which were further oxidized to Sn(IV). The electrolyte characteristics reported by the authors limit its stability and significantly restrict its industrial application. In addition, difficulties related to the complexation behavior and solubility of some metal tartrate compounds may arise.

Methanesulfonic electrolytes combine several favorable properties: high electrical conductivity, high solubility of methanesulfonates, low volatility [20], excellent biodegradability, lower environmental impact, and the possibility of operation at high current densities [21]. Therefore, methanesulfonic acid (MSA)-based solutions may represent a good alternative to other electrolytes. However, studies in this field remain limited.

In [22], electrodeposition of Cu-Sn alloys from a methanesulfonic electrolyte containing benzyl alcohol was investigated. However, an insoluble platinum anode was used, and therefore the study does not reveal the possibility of using soluble anodes of a similar alloy.

The study of electrochemical dissolution and recovery of Sn from PCBs in methanesulfonic acid solution was presented in [23]. A tin-coated PCB was used as the anode, and tin was removed by a one-step process and deposited on the cathode during electrolysis. Optimal conditions were identified: 40°C, 60 g/L Sn^{2+}, 100 g/L methanesulfonic acid, an interelectrode distance of 60 mm, and a current density of 200 A/m2. A significant limitation of this work is that only one element was processed, whereas, as shown above, PCBs contain at least several metals.

In [24], the authors investigated the dissolution of a multicomponent solid superalloy, including dissolution in a methanesulfonic electrolyte containing chlorides. A high dissolution rate in this electrolyte and a close correspondence between the electrolyte composition and the original alloy composition for the monitored elements were demonstrated. However, the composition of the nickel-based superalloy differs significantly from that of recycled alloys obtained from PCBs.

Summarizing the studies [9–19, 22–24], various solutions and electrolytes have been proposed for the processing of copper, tin, and their alloys. Sulfuric acid electrolytes are frequently used, although they have several disadvantages. Information on the processing of copper, tin, and their alloys in methanesulfonic electrolytes is limited. This is especially true for multicomponent alloys containing both Cu and Sn. Therefore, the present study aims to fill this gap by investigating the anodic dissolution behavior in a methanesulfonic electrolyte and comparing it with conventional sulfuric acid electrolytes.

3. The aim and objectives of the study

The aim of this study is to determine the regularities of electrochemical dissolution of a multicomponent alloy obtained as a product of PCB recycling in sulfuric acid and methanesulfonic electrolytes. This will make it possible to evaluate the selectivity of dissolution of individual alloy components, as well as changes in the surface composition after electrochemical treatment. Thus, the study will allow assessment of the feasibility of using electrochemical dissolution as the first stage in processing complex metallic fractions of electronic waste, thereby further simplifying separation and recovery processes for valuable components.

To achieve this aim, the following objectives were accomplished:

– to investigate the electrochemical dissolution of an alloy obtained as a product of printed board recycling in electrolytes based on sulfuric acid and methanesulfonic acid;

– to evaluate the influence of electrolyte type on the dissolution rate and selectivity of individual alloy components.

4. Materials and Methods

4. 1. The object and hypothesis of the study

The objective of the study is the electrochemical dissolution of a multicomponent alloy obtained from the recycling of printed electronic boards (PCBs). The main components of the investigated alloy are Cu, Sn, Pb, Ni, and other metals typically present in metallic parts and components of electronic waste.

The electrolyte composition may determine the rate, selectivity, and mechanism of electrochemical anodic dissolution of individual components of a multicomponent metallic alloy. The hypothesis of the study is that the use of methanesulfonic electrolytes may change the dissolution mechanism due to the increased solubility of some metal ions and depassivation of surface layers compared to the more commonly used sulfuric acid electrolytes. Such an approach may provide faster, more efficient, and more selective dissolution of individual alloy components, as well as simplify the subsequent recovery and separation of valuable metals from the electrolyte in an environmentally friendly way.

A limitation of this study is the difficulty of directly evaluating the combined influence of multiple factors on the kinetics and quantitative characteristics of electrochemical alloy dissolution when a new type of electrolyte is used.

4. 2. Materials and reagents

Distilled water was used to prepare all solutions. H_2SO_4 and CH_3SO_3H of analytical grade were used. Electrolytes were prepared by dilution of concentrated H_2SO_4 with a density of 1.22 g/cm^3 and 70% CH_3SO_3H.

Pieces of the alloy obtained after thermal processing of PCBs were washed with tap water, distilled water, acetone, and ethanol before use.

4. 3. Methods for characterization of the alloy

Analysis of alloy chemical composition.

The elemental composition of the alloy surface was determined by non-destructive X-ray fluorescence (XRF) using a Rigaku NEX CG energy-dispersive X-ray fluorescence spectrometer (Rigaku Corporation, Japan). Measurements were carried out in a helium atmosphere at an X-ray tube voltage of 50 kV.

Analysis of electrolyte composition.

Determination of Sn.

A 5 mL aliquot of the solution under study was transferred into a 250 mL conical flask using a pipette. Then, 40 mL of 1 M methanesulfonic acid solution, 30 mL of 20% $NaHCO_3$ solution, and 20–30 drops of a 1% starch solution were added. Titration was carried out with a 0.01 N iodine solution until a blue color appeared and remained stable for 30 s. The concentration of tin (CSn) (g/L) was calculated using eq. (1)

$$C_{\text{Sn}} = \frac{C_{I_2} \cdot V_{I_2} \cdot M\left(1/2\right)_{\text{Sn}}}{V_s}, \quad (1)$$

where $\tilde{N}_{I_2}$ – normality of the I_2 solution, mol-eq/L;

V_{I_2} – volume of the I_2 solution consumed during titration, mL;

$M(1/2)_{Sn}$ – equivalent molar mass of tin, 59.35 g-eq./mol;

V_s – sample volume.

Determination of the total concentration of Cu and Ni.

A 0.3–0.5 mL aliquot of the analyzed solution was transferred into a 250 mL conical flask. Then, 50 mL of distilled water, 10 mL of ammonia buffer solution, and 30–40 mg of a murexide-sodium chloride mixture (1:500) were added, followed by thorough mixing. Titration was carried out with a 0.1 N EDTA solution (Trilon B) until the color changed from brown-yellow to violet. The total concentration of copper and nickel ions (C_{Cu+Ni}) (mol-eq/L) was calculated using eq. (2)

$$C_{\text{Cu+Ni}} = \frac{C_{\text{EDTA}} \cdot V_{\text{EDTA}}}{V_s}, \quad (2)$$

where C_{EDTA} – concentration of EDTA (Trilon B), mol-eq/L;

V_{EDTA} – volume of EDTA solution consumed during titration, mL;

V_s – volume of the analyzed solution sample, mL.

Determination of Ni.

A 0.1 mL aliquot of the analyzed solution was transferred into a 100 mL volumetric flask. Then, 20 mL of distilled water and 2 mL of a 10% aqueous ammonium persulfate solution were added. The solution was mixed and left for several minutes. After that, 1 mL of a 25% aqueous ammonia solution (pH ≥ 9) and 1 mL of a 1% dimethylglyoxime solution prepared in 5% aqueous KOH were added. The solution developed a pink color. The volume was adjusted to the mark with distilled water, and the mixture was mixed thoroughly.

The optical density of the obtained solution was measured relative to distilled water using a KFK-2 photoelectric colorimeter at $\lambda = 490$ nm in a cuvette with an optical path length of $l = 3$ cm. The nickel concentration was determined using a calibration curve.

Determination of Cu.

The copper concentration (g/L) was calculated using eq. (3)

$$C_{Cu} = \left(C_{Cu+Ni} - C_{Ni}\right) \cdot M\left(1/2\right)_{Cu}, \qquad (3)$$

where $M(1/2)_{Sn}$ – equivalent molar mass of copper, 31.8 g-eq/mol;

C_{Cu+Ni} – total concentration of copper and nickel ions, mol-eq/L;

C_{Ni} – nickel concentration determined by photocolorimetric analysis, mol-eq/L.

Electrochemical studies.

The electrochemical behavior of the alloy was investigated using an MTech SPG-500fast potentiostat (MTech, Ukraine). A graphite electrode was used as the counter electrode, and an Ag|AgCl electrode in 3.5 M KCl was used as the reference electrode. Measurements were carried out at a temperature of 18°C.

Cyclic voltammograms (CVs) were recorded at scan rates of 2 and 20 mV/s within the selected potential window. Each voltammogram consisted of 5 complete cycles.

Before each experiment, the sample surface was cleaned with 80 μm abrasive paper and degreased. To determine the specific electrochemical activity, the exposed electrode area was standardized by partially covering the surface with a PTFE film, leaving only a defined active area exposed to the electrolyte.

Evaluation of the specific electrochemical dissolution rate.

The calculations were performed by numerical integration using a computer program, following the procedure described in detail in [25].

5. Results of the study of anodic dissolution of an alloy obtained from recycled printed circuit boards

5. 1. Evaluation of the electrochemical characteristics of the investigated alloy in sulfuric acid and methanesulfonic electrolytes

The obtained cyclic voltammograms are presented in Fig. 1. For each electrolyte, two scan rates differing by one order of magnitude were used to evaluate the influence of current on the electrochemical processes. The obtained data make it possible to assess the dissolution kinetics of the alloy.

For 1 M H_2SO_4 (Fig. 1, *a, b*), low current densities are observed in the potential range from −0.3 to 0 V. At potentials above 0 V, the current increases sharply after +0.2 V. During the reverse potential scan, a plateau consisting of two peaks appears in the range from 0 to +0.2 V. In the negative potential region, a gradual increase in cathodic current density is observed.

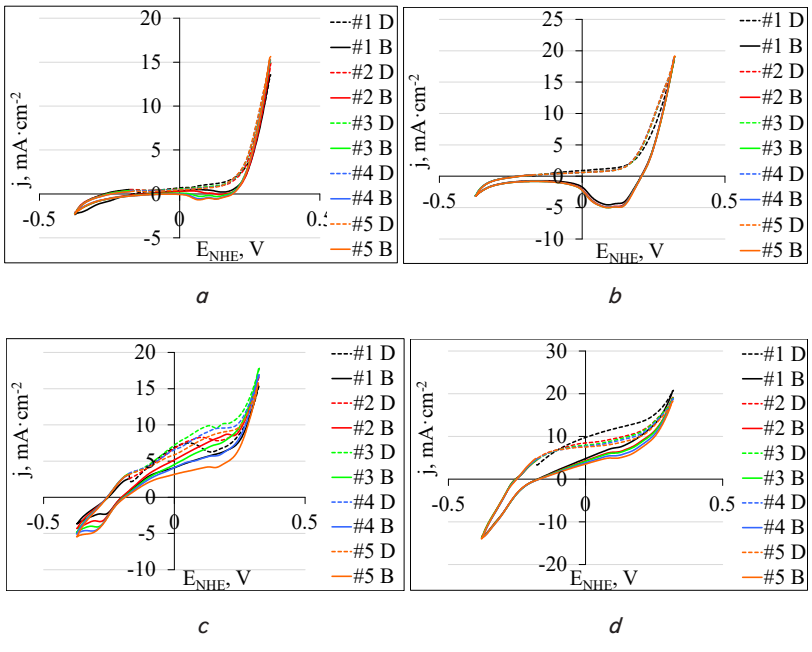

Fig. 1. Cyclic voltammograms showing current density, j (mA·cm^{-2}), versus potential, E (V), obtained for the alloy recovered from recycled printed circuit boards (PCBs) (# — cycle number; B and D — forward and reverse scan directions): *a* — in 1 M H_2SO_4 at a scan rate of 2 mV·s^{-1}; *b* — in 1 M H2SO4 at a scan rate of 20 mV·s^{-1}; *c* — in 1 M CH_3SO_3H at a scan rate of 2 mV·s^{-1}; *d* — in 1 M CH_3SO_3H at a scan rate of 20 mV·s^{-1}

An increase in the potential scan rate leads to an increase in current density, which corresponds to the classical understanding of the influence of potential change rate on the current (current density).

In contrast to 1 M H_2SO_4, the behavior of the alloy in a methanesulfonic acid electrolyte of the same concentration is significantly different. The general trends are an increase in current density over the entire potential range and a shift of the whole curve toward the anodic region. Thus, oxidation processes are more pronounced in the methanesulfonic acid electrolyte. In addition, when the scan rate increases, the visible electrochemical processes almost disappear.

For the cyclic voltamograms shown in Fig. 1, numerical integration was performed to obtain the specific amounts of electricity associated with the anodic process (Fig. 2). In all cases, the amount of electricity related to oxidation in 1 M CH_3SO_3H is higher than that obtained in 1 M sulfuric acid electrolyte. It should also be noted that the values change only slightly from cycle to cycle for the same electrolyte composition.

A comparison of the average anodic specific amounts of electricity for the two electrolytes demonstrates a clear advantage of the methanesulfonic electrolyte: the oxidation rate is 2–3 times higher than that observed in the sulfuric acid electrolyte (Fig. 3).

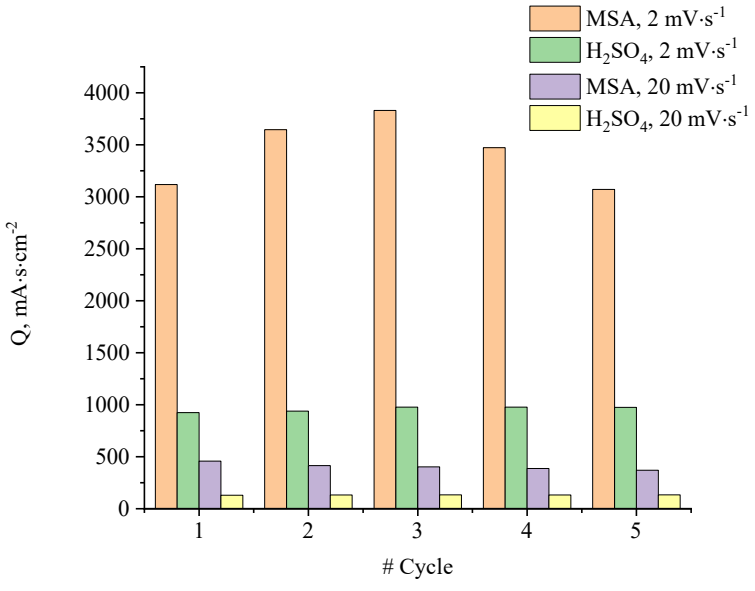

Fig. 2. Changes in the specific amounts of electricity during each cycle of the cyclic voltammograms associated with alloy dissolution in different electrolytes and at different potential scan rates

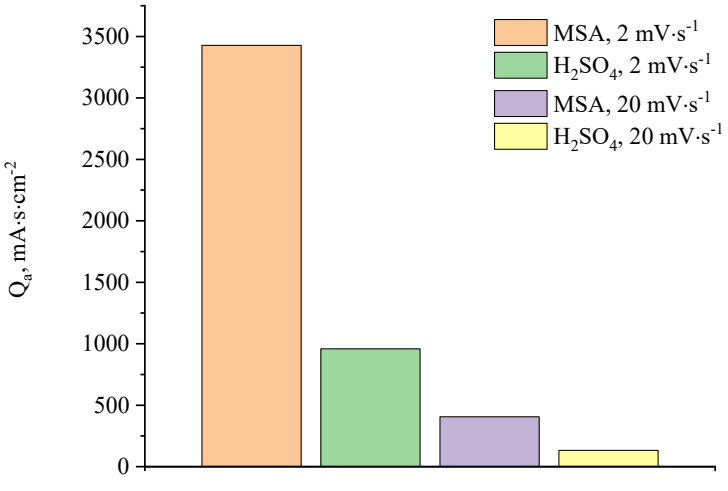

Fig. 3. Average values of the specific amounts of electricity for 5 cycles of the cyclic voltammograms associated with alloy dissolution in different solutions and at different scan rates

Since alloy dissolution in the methanesulfonic electrolyte proceeds much more actively and this parameter is the main criterion for electrolyte selection, further investigations were focused on this electrolyte and on evaluating its possible selectivity.

5. 2. Determination of changes in the composition of the electrolyte and alloy during anodic dissolution in methanesulfonic electrolyte

According to the X-ray fluorescence analysis, the initial composition of the investigated alloy obtained after PCB recycling was characterized by a high content of Cu (51.4 wt.%), Sn (22.6 wt.%), and Ni (17.7 wt.%), as well as smaller amounts of Pb (4.73 wt.%) and Fe (3.47 wt.%). This confirms the complex multicomponent nature of the secondary metallic material.

During anodic dissolution of the alloy in the methanesulfonic electrolyte, the formation of a deposit on the sample surface was observed. According to X-ray fluorescence analysis, the Sn content in the surface layer increased to 34.4 wt.%, while the Pb content increased to 10.2 wt.%. Thus, it can be assumed that this layer consisted mainly of Sn-containing compounds, which may indicate the formation of sparingly soluble tin hydrolysis products, including hydrated SnO_2 or metastannic acid.

After anodic dissolution in 1 M methanesulfonic electrolyte and removal of the above-mentioned deposit, a decrease in Cu content from 51.4 to 38.5 wt.% and in Pb content from 4.73 to 1.37 wt.% was observed. At the same time, a relative enrichment of the surface with Sn and Ni occurred, their contents increasing to 30.6 and 26.1 wt.%, respectively. This may indicate a selective character of alloy dissolution and the possible formation of a surface layer enriched with less actively dissolving components.

The electrolyte composition was monitored in the current density range of 0.5–1 A/dm^2 (Fig. 4). The final electrolyte composition showed only a weak dependence on current density. No clear trend was observed during the experiments. Therefore, the observed variations may be related to local inhomogeneities of the alloy and the additive effect of the analytical methods used.

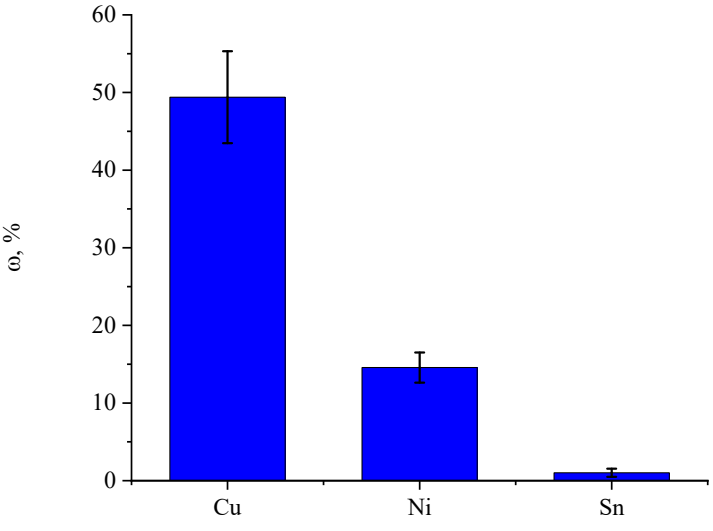

Fig. 4. Average ratio of the monitored components in the methanesulfonic electrolyte relative to the alloy mass loss after electrolysis in the current density range of 0.5–5 A/dm^2

The error bars calculated for the current density range of 0.5–5 A/dm^2, which differs by one order of magnitude, indicate a relatively small possible deviation (Fig. 4). It should also be noted that the ratio between Cu and Ni corresponds well to the ratio of these metals in the alloy (approximately 3:1).

6. Discussion of the results of alloy dissolution obtained from recycled printed circuit boards

The results indicate that the anodic dissolution behavior of a multicomponent alloy depends on both the alloy's phase and elemental composition [26] and the nature of the electrolyte [27]. In the sulfuric acid medium, the anodic currents were lower (Fig. 1, *a*, *b*) than in the methanesulfonic electrolyte (Fig. 1, *c*, *d*). This indicates less intensive dissolution of the alloy components. It should be noted separately that the potential window was selected in such a way that anodic oxygen evolution did not occur and therefore did not introduce an error due to a deviation from current efficiency (the equilibrium oxygen evolution potential at pH = 1 is $E \approx 1.23$ V). At the same time, the cyclic voltammograms showed regions of a sharp current increase when the potential was shifted in the anodic direction, as well as peaks during the reverse scan. Such behavior may be related to the sequential dissolution of individual alloy components, restructuring of surface oxide-salt layers, and partial reduction of surface compounds or metal ions formed during the anodic scan. The latter may be associated with nickel [28], which is prone to passivation, and tin [29], which may form sparingly soluble gel-like precipitates of hydrated oxides.

Unlike the sulfuric acid electrolyte, higher current densities (Fig. 1, *c*, *d*) and larger specific amounts of electricity associated with the anodic process (Fig. 2, 3) were observed in 1 M CH_3SO_3H. This indicates more intensive electrochemical dissolution of the alloy in the methanesulfonic medium. Most likely, this difference is related to the higher solubility of certain metal methanesulfonates present in the alloy. This, in turn, may hinder the formation of dense, sparingly soluble surface layers compared to the sulfuric acid medium.

Analysis of the electrolyte composition after electrolysis showed that Cu was the main component transferred into solution. The average copper content, normalized to alloy mass loss, was about 49.4%, whereas the corresponding values were about 14.6% for Ni and about 1.0% for Sn. This indicates preferential dissolution of copper and a much less intensive transfer of tin into the electrolyte. The absence of a clear monotonic dependence of electrolyte composition on current density in the range of 0.5–5 A/dm^2 may be related to the nature of soluble metal compounds (Fig. 4).

The results of X-ray fluorescence analysis of the surface are in good agreement with the electrolyte analysis data. After anodic dissolution in the methanesulfonic electrolyte, enrichment of the surface with Sn and Ni was observed, together with the formation of a deposit enriched in Sn and Pb. This indicates that some alloy components do not dissolve proportionally to their content in the initial material but remain on the surface as sparingly soluble products or passivating layers. For tin, this effect may be associated with the formation of hydrated SnO_2 or metastannic acid, while for lead, it may be related to the formation of sparingly soluble surface compounds.

It should be noted that a specific feature of this study is the use of a methanesulfonic electrolyte for the anodic dissolution of a multicomponent alloy simultaneously containing copper, tin, nickel, lead, and iron. A literature search did not reveal studies closely related to the approach presented here. Thus, the study expands the practical applications of methanesulfonic acid. Since this acid has high electrical conductivity, the use of such an electrolyte may reduce the cell voltage and, consequently, the specific energy consumption of electrochemical dissolution. On the other hand, the mechanisms described here may accelerate the process due to destruction of passive films and the possibility of operating at higher current densities because of the good solubility of some ions. An additional advantage of the selected electrolyte is its improved environmental performance.

Thus, the methanesulfonic electrolyte provides more intensive anodic dissolution of the investigated alloy compared to the sulfuric acid electrolyte, although the process also exhibits some degree of selectivity. Copper is transferred into solution most actively, whereas tin and lead mainly accumulate in the surface layer or in solid products. From a practical point of view, this may be both a limitation and an advantage, since it allows partial separation of components already at the first stage of electrochemical processing.

For industrial implementation of such an approach, it is necessary to consider the possible formation of surface passive layers, solid and gel-like insulating electrolysis products, and subsequent chemical reactions. Their influence may be reduced by mechanical renewal of the metal surface, for example by mixing alloy pieces in titanium drum electrolyzers or by applying ultrasonic treatment. The latter may also improve process performance due to faster removal of metal ions from the electrode surface. Solid products, including tin-containing precipitates, may be removed from the electrolyte by continuous filtration. This may help maintain electrolyte stability and improve the efficiency of further electrochemical dissolution.

Potential applications include metal recycling facilities, including enterprises specializing in the complete recycling of electronic and electrical equipment. The application of the obtained results requires compliance with the parameters

reported in this study, including current density ranges, electrolyte concentrations, and alloy composition.

Potential benefits of implementing the proposed approach include improved environmental conditions for plant personnel, reduced environmental impact of recycling facilities, lower processing costs, and higher processing rates.

Future work may include investigation of the influence of acid concentration and the use of additional depassivating additives, particularly chloride ions. One limitation of the present study is the limited number of ions analyzed in the electrolyte after anodic dissolution.

7. Conclusions

1. A comparative evaluation of alloy dissolution, where the alloy was obtained as a product of PCB recycling, was carried out in two electrolytes: sulfuric acid and methanesulfonic acid-based electrolytes. It was shown that the dissolution rate in the methanesulfonic electrolyte is 2–3 times higher.

2. It was established that during dissolution of the alloy in 1 M CH_3SO_3H within the current density range of 0.5–5 A/dm^2, Cu and Ni are transferred into solution. In contrast, Sn and Pb, although oxidized, form sparingly soluble compounds on the metal surface. Thus, the anodic dissolution process in the methanesulfonic electrolyte exhibits a certain degree of selectivity.

Conflict of interest

The authors declare no conflicts of interest regarding this study, including financial, personal, authorship-related, or other conflicts that could have influenced the study or the results presented in this article.

Data availability

The manuscript has no associated data.

Use of artificial intelligence tools

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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