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IEEE
2022-12-01

Holmström , A , Pudas , T M , Hyvönen , J T J , Sillanpää , T O N , Lassila , P J , Mäkinen , J M K , Mizohata , K , Kuronen , A , Kotiaho , T , Salmi , A & Haeggström , E 2022 , Identifying Regions-of-Interest and Extracting Gold from PCBs Using MHz HIFU . in 2022 IEEE International Ultrasonics Symposium (IUS) . IEEE , pp. 1-3 , 2022 IEEE International Ultrasonics Symposium (IUS) , Venice , Italy , 10/10/2022 . https://doi.org/10.1109/IUS54386.2022.9957863

http://hdl.handle.net/10138/355160
https://doi.org/10.1109/IUS54386.2022.9957863

Identifying Regions-of-Interest and Extracting Gold from PCBs Using MHz HIFU

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***Abstract* — Increased digitalization and technological development raises the demand for rare and precious metals (RPM). Due to their rarity, mining RPMs from the earth is becoming increasingly difficult. Traditional urban mining methods to recover RPMs from printed circuit boards (PCB) need to separate the RPMs from non-metallic substances, e.g. plastic. This separation requires toxic substances and causes unwanted and toxic by-products and emissions. The ability to identify regions-of-interest on PCBs, i.e. the gold pads, and to extract RPMs from only the desired areas would reduce the need for toxic substances. In this study, a single 12 MHz high-intensity focused-ultrasound transducer was used to 1) image a PCB to locate the gold pads, and 2) to subsequently induce inertial cavitation to remove gold from three extraction areas on the selected gold pad. The sonication was performed in water without additional chemicals. Gold removal was verified by imaging the pad with a coded-excitation scanning acoustic microscope (f_c = 375 MHz). Average areas and volumes of the three extraction regions were $A = (12.2 \pm 0.5)\cdot 10^3$ µm² and $V = (18 \pm 2)\cdot 10^3$ µm³, respectively. The total amount of removed gold and nickel (from beneath the gold plating) from all three extraction areas was estimated to $m_{Au,tot}$ = (570 ± 20) ng and $m_{Ni,tot}$ = (440 ± 30) ng. This study constitutes a first step towards more environmentally friendly, non-toxic urban mining of RPMs.**

Keywords—Urban mining, cavitation erosion, MHz high-intensity focused ultrasound

I. Introduction

Increasing digitalization and technological development has benefitted humanity as increased prosperity, longevity, and health. However, this development has also increased the demand for electronic devices, which contain printed circuit boards (PCBs). Rare and precious metals (RPMs), for example gold, are used in PCBs because of their excellent physical and chemical properties, such as corrosion resistance, desirable thermoelectrical properties, and high conductivity. Thus, RPMs are still used despite their rarity, as they cannot easily be substituted for other materials. Due to their rarity, mining of RPMs from the earth is becoming increasingly difficult. For example, the total gold reserves have been estimated to approx. 244 000 t, of which 57 000 t are unexploited [1]. The global gold mine output in 2018 was 3310 t/year, while only 1178 t of gold was sourced from recycling [2]. At this pace, all gold would be mined within 20 years. To solve this, urban mining from electronic waste, e.g. discarded PCBs, is an expanding field [3, 4]. Electronic waste contains high concentrations of RPMs and could thus be used to enrich RPMs back into usable form [3, 4].

Traditional urban mining methods are faced with the task of separating RPMs from non-metallic materials found in PCBs, e.g. plastic casings of components. The separation process usually comprises three processing steps, as no single process is efficient enough as a stand-alone method: mechanical pre-processing, pyrometallurgy, and hydrometallurgy [3, 4]. The mechanical pre-processing constitutes e.g. manual PCB disassembly and/or PCB crushing [3]. In the pyrometallurgic step, the pre-processed PCBs are incinerated to separate the metals from other materials. This process causes harmful emissions and toxic waste [3]. In the final hydrometallurgic process, metals are leached. The leaching uses substances which cause toxic fumes or by themselves are highly toxic or caustic, for example cyanide and acids [3, 4]. Bioleaching, which utilizes microorganisms or their metabolites for leaching, is an emerging field that would be environmentally friendly [3, 4]. Unfortunately, leaching rates are low and the microorganisms are easily poisoned by toxic by-products, stopping the leaching process. Hence, bioleaching is currently only performed on a laboratory scale.

In this study, we propose a novel and environmentally friendly urban mining solution: Using high-intensity focused ultrasound (HIFU), in water, to first identify regions-of-interest (ROIs) on PCBs, i.e. locate the gold pads, and to

This work was funded by the Academy of Finland (grant 347459).

subsequently extract gold from the desired areas using HIFU-induced inertial cavitation. Identifying the gold pads and removing gold only from them eliminates the need for further separation of metals from non-metallic materials. HIFU-induced inertial cavitation can be applied in water, without any chemicals or toxins, and is a well-known material erosion phenomenon that has been utilized e.g. on aluminium [5, 6] and in lithotripsy to break kidney stones [7]. We used a 12 MHz custom-built HIFU transducer to obtain both imaging and material extraction capability. Material removal was quantified with a coded-excitation scanning acoustic microscope (CESAM) [8, 9].

II. Methods

A. Experimental Setup and Sample

The HIFU setup is shown in Fig. 1. The 12 MHz HIFU-transducer contained a custom-built piezo bowl (F5265018, Meggitt A/S, Kvistgaard, Denmark) (bandwidth 2 MHz, element diameter 1.9 cm, focal distance 1.5 cm, focal width 140 µm). Signals were generated with an arbitrary waveform generator (FG31052 SERIES, Tektronix, Oregon, USA) and sent to a power amplifier (500A100A, Amplifier Research, Pennsylvania, USA, bandwidth 10 kHz–100 MHz) at either low (imaging) or high (material extraction) settings. Echoes were recorded with an oscilloscope (PicoScope 5442D, Pico Technology, Cambridgeshire, UK) through a 100x attenuating voltage probe (TT-HV250, TESTEC Elektronik GmbH, Hesse, Germany) and saved to a computer. A 3D translation stage (Techno Isel router table, Isel Germany AG, Hesse, Germany) was used to scan the sample during imaging. Both imaging and extraction was performed in reverse-osmosis purified water (RiOs Essential Water Purification Systems, Milli-Q, Hesse, Germany) that had been under vacuum for 20 min. This was done to remove contaminants and to control the concentration of dissolved gas, as both particulates and gas bubbles act as nucleation sites for cavitation.

The sample was an obsolete PCB containing gold pads (Fig. 2A). Gold pads comprise a copper base, coated by a 6 µm intermediate nickel layer and coated with gold. As the gold-layer thickness on gold pads varies depending on the manufacturing method, the gold layer was measured using Rutherford backscattering spectrometry (^{7}Li-beam, beam energy 5 MeV) to be (870 ± 20) nm.

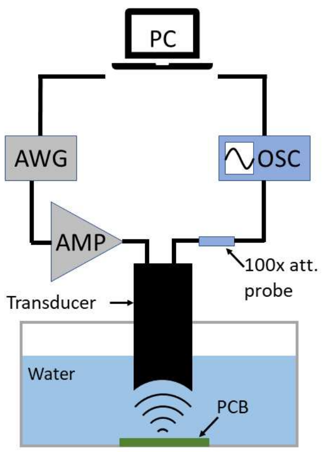

Fig. 1. Schematic of HIFU-setup. Signals are transmitted from the computer (PC) via an arbitrary waveform generator (AWG) to a power amplifier (AMP) at low (imaging) or high (extraction) settings and to a 12 MHz focused transducer. In imaging, sample echoes are recorded with the oscilloscope (OSC) as the sample is scanned with 3D translation stages.

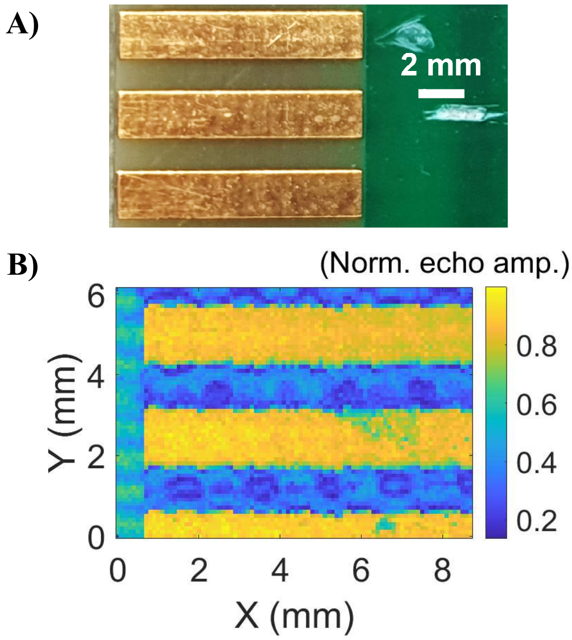

Fig. 2. PCB sample. A) Photograph of the gold pads. B) Amplitude map of the sample imaged with the HIFU-transducer.

B. Identifying Regions-of-Interest

A 6 mm x 8 mm area of the gold pads was scanned with the HIFU-transducer (f = 12 MHz, 20-cycle bursts, 100 µm step size). An amplitude map was constructed from the echoes (Fig. 2B), showing higher reflection amplitude from the gold pads, distinguishing them from the board.

C. Gold Extraction

One gold pad was selected for gold extraction. Three separate extraction areas, 520 µm apart, were sonicated. Each area consisted of a 5 x 5 grid of sonication spots with 20 µm spacing (area 80 µm x 80 µm), each sonication was performed with constant acoustic parameters: f = 12 MHz, 30 cycles/burst, 250k bursts, PRF = 1 kHz, P_{PPP} = 40 MPa). Extraction was quantified using a coded-excitation scanning acoustic microscope (CESAM) [8, 9] with a 375 MHz transducer (bandwidth 140 MHz, beam width 2.5 µm, scanning step size 1 µm). The Tx-signal was a 300–500 MHz linear chirp with 1 µs burst length (Gaussian envelope). The measured topography map was used to calculate the amount of removed material from each extraction area.

III. Results and Discussion

The topography map and depth profile of one extraction area is shown in Fig. 3 as an example. For each extraction area, a ROI-mask, containing only the areas of cavitation extraction (including small cavitation pits), was made manually. The surface zero-level was determined, and the depth profile was used to calculate the amount of removed gold and nickel. The average extraction areas, volumes, and amounts of removed gold and nickel were calculated to determine the repeatability of the extraction (average ± standard deviation): A = (12.2 ± 0.5)·10^{3} µm^{2},

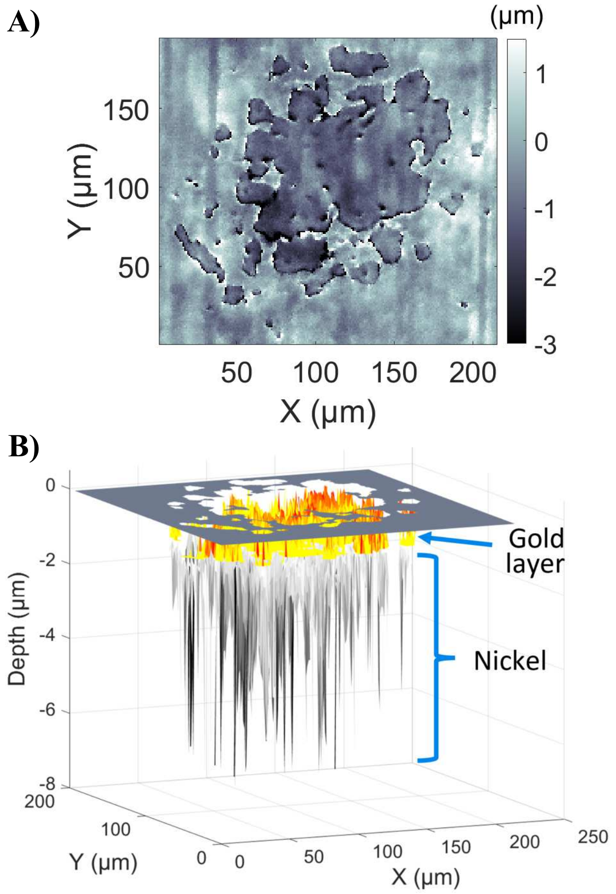

Fig. 3. CESAM topography map of one extraction area. A) Top view showing the shape of the cavitation extraction. B) Depth profile showing extraction depth into gold and nickel.

$V = (18 \pm 2)\cdot 10^3$ μm³, $m_{Au} = (190 \pm 20)$ ng and $m_{Ni} = (150 \pm 30)$ ng. The variation in volume was larger than that in area, because the bottoms of the extraction areas were uneven, *cf.* Fig. 3B. The uncertainty in removed gold and nickel masses are attributed to the uncertainty in the gold-layer thickness (± 20 nm). The standard deviation of the calculated masses and the uncertainty caused by variation in volume were orders of magnitude smaller than the contribution from the layer-thickness uncertainty. Finally, the total amount of removed material from all three extraction areas was calculated, which was $m_{Au,tot} = (570 \pm 20)$ ng and $m_{Ni,tot} = (440 \pm 30)$ ng.

The extracted material was not collected in this study. To collect the gold particles, the extracted particulates could be filtered from the water. Nickel is ferromagnetic and could thus easily be separated from gold. In the literature, one can find more complex methods for separating gold particles from complex water solutions, such as metal-organic-framework/polymer composites, which have been successfully used to collect 99 % of gold particles in river water [10].

Further work is needed to improve both the benefit-cost ratio and energy efficiency of this method. An estimate for the required removal work of this total amount of material was made from the cohesive energy of gold and nickel, which amounted to 4.4 mJ. The used electric energy was calculated from measured power being delivered to the transducer, which amounted to 3.8 kJ. Losses can occur in many parts of the process, for example as losses in the transducer, absorption in water, and bubble shielding [11] causing acoustic energy to be reflected rather than attributing to desired inertial cavitation. Though the energy efficiency is low, the benefit-cost ratio, i.e. the monetary value of the extracted gold divided by the cost of the used electricity, was 12 %. As such, the method is not yet cost effective, but this ratio is clearly higher than the energy efficiency, hinting that the method could be economically feasible with further developments. As seen in Fig. 3B, nickel was also removed superfluously. Only 16 % of the extraction area had pure gold removal, without any nickel. Optimizing the sonication parameters to only remove gold or using a different transducer-sample geometry (e.g. transducer at an angle, not perpendicular, possibly inducing a peeling effect) could improve this. Yet another possibility could be to use a lower centre frequency HIFU-transducer, which would result in a larger focal region and a lower cavitation threshold. The current 12 MHz transducer has a 140 μm focus, providing imaging capability, but the small focal region also restricts the area where extraction can occur. Imaging with a lower frequency transducer might be improved by using 2nd or 3rd harmonic imaging, thus achieving a reasonable trade-off between imaging and extraction capability.

IV. Conclusion

Gold extraction from an obsolete PCB – from only desired regions-of-interest – was achieved in water (without added chemicals or toxins) using a single 12 MHz HIFU-transducer. This demonstrates a first step towards more environmentally friendly, non-toxic urban mining of rare and precious metals.

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