Recovery of precious (Au, Ag, Pd, Pt) and other Metals by e-scrap processing

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The professional paper is a brief report of an investigation results to be adopted into production. In fact it is a resume of a study on the idea of e-scrap processing and metal production in Mining and Metallurgy Institute Bor, Serbia, based on its expert team investigations of the relevant literature and practice evidences and own research results. The investigations results are presented shortly in the First part of the paper where the chosen technological solution is described including the basic parameters for economic analysis. The second part of the paper is a resume of the economic analysis that approves benefits of the e-scrap processing and profitability of the metals production. Conclusion signifies the investigations and the study importance for realization of a project expected to generate important ecological and economical benefits.

Key words: e-scrap processing; Au; Ag; Pd; metal production; investigation; technology; economy.

INTRODUCTION

E-scrap processing of based metal production in Mining and Metallurgy Institute Bor, Serbia is a project based on serious considerations of the actual trends in related technology and economy fields. As an (Research and Development) R&D institution, we have adequate experience, staff and equipment for the processing and profitability production.

As the e-scrap is one of the growing global ecological problems and its processing is in the focus of the researchers and others interested in the problem solution all over the world. Growing electronic industry production in the last decades caused the e-scrap quantity increase. E-scrap contains number of different metals such as copper, zinc, iron, precious metals, cadmium, lead, mercury and other materials such as plastics, glass and organic materials [1, 2]. Some of the metals are well marketable according to its prices trends [3] and the metal production based on e-scrap processing appears to be profitable.

According to the actual reports e-scrap quantity has been gradually rising at the annually rate of 3-5% which means 10-50 billion tones every year [4]. Global recycling rate of e-scrap is variable: while it is 86% in Japan, 50-60% in EU and 12-13% only in Serbia [5]. To raise the e-scrap recycling rate in Serbia it is necessary to organize it better from the initial phase of gathering and sorting to the final processing and supporting activities. It is also important to organize it in accordance with the European Union legislation. Aiming that, Serbian Government has adopted the Law on Waste Management and the Law on Packaging and Waste Packaging [6]. Required framework for the e-scrap management in Serbia including its gathering and processing has been established.

In the aim to keep step with the actual trends and the situation in the field, Mining and Metallurgy Institute Bor, with its reach R&D experiences, qualified staff and equipments capacities (Figure 1), has undertook approximate investigations and framed the project of e-scrap processing and metal production as a part of its medium-term development plan. The project is planned to be realized and is expected to be important from both economical and ecological aspects.

E-SCRAP PROCESSING AND METAL PRODUCTION TECHNOLOGY

Pilot Plant Equipment.

All tests were performed in pilot plant presented on Figure 1.

Description of the Accepted Technology

Printed Circuit Board – PCB as the basic row for the special metal production was analyzed first. Chemical composition of PCB is shown in Table 1.

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Table 1. Chemical composition of PCB

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
<th>Element</th>
<th>%</th>
<th>Element</th>
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<td>0.001</td>
<td>Mg</td>
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</table>

Our investigations of seven types of PCB have led to the following conclusion: the average metal part of the PCB content is 28.6% including the copper dominating 22.6%. Precious metals content was considered as the most important for their share in the market value of the metal production was estimated to be 65-80%.

Technological process of the computer e-scrap recycling starts with the following phases:
- Used computer equipment transportation
- Computer equipment acceptance
- Computer equipment storage

The process continues with the phase of disassembling of the components that includes:
- Probity and functionality check
- Disassembly
- Separation
- Temporary storage of components, recyclable and non recyclable
- Some components transportation for further processing and/or refuse

The PCB processing is the most complex phase of the technological process for its complex composition meaning variety of materials. The processing phase includes the processes of pyrometallurgy, electrolysis and refinement shortly described below.

**Pyrometallurgy**

In the preparation phase it is necessary to remove the capacitors containing very harmful and toxic materials. After grinding to the required grain size and separation of plastic, first follows magnetic separation and then separation of aluminum parts. Lead and tin in solder are very harmful for the further processing, especially in the electrolytic refining of copper. These metals must be removed by low-temperature heating process (320–350°C). Melting and casting of copper anode containing collected precious metals was performed in the Electric arc furnace-Birlac (Figure 1a) by conventional techniques for copper.

**Electrolytic refining**

Electrolytic refining of anodes, obtained by melting e-scrap was performed in two cathode periods in new pilot plant for electrolytic refining of anode with non-standard chemical composition (Figure 1b) in the aim to obtain copper cathodes of the commercial quality (99.99% Cu). The anode sludge is subject to further hydrometallurgical processes in order to obtain precious metals of commercial quality.
Refinement

The anode slime obtained by electrolytic refinement of the copper anodes with high content of precious metals was processed in the Laboratory for refinement of precious metals in the special 100 dm³ glass reactors (Figure 1c). The first phase of the refinement is the process of decopperisation of anode slime by leaching with diluted sulfuric acid in the presence of oxygen as the oxidant. After the process of decopperisation, the anode slime contains max. 2% of copper. Anode slime without copper is a raw material for the next stages of processes in the aim to obtaining gold, silver and palladium.

Two illustrations of the described processing technology are presented on the following figures. On Figure 2 is shown technology block scheme proposed by Park and Fray [7] and on Figure 3 adopted technology in Mining and Metallurgy Institute Bor.

During the pyrometallurgical treatment certain metals losses are inevitable (Zn and Pb mainly). These metals evaporate with the melting gases or, eventually, through the slag. The melting losses of the metals are about 2.5%. After the melting phase 11.5 t of copper anodes (11.8×0.975) contains 11.2 t of copper and 0.3 t of precious metals with impurities.

Metal recovery by the hydrometallurgical treatment of metal parts is: for copper ≈ 99%, for gold ≈ 98%, for silver ≈ 93% and for palladium ≈ 98%. This means that electrolysis will have at disposal: 11.0/12 = 0.92 t of anodes per month, while the average weight of anodes will be 958/28 = 32.86 kg. (28 anodes is the electrolysis capacity, which annually is 336 anodes) [8].

Electrolysis

After melting and casting the electrolysis is provided with 11 tons of anodes, with 95% Cu-10.45 t.

The content of precious metals in the anodes is: max 0.1% - 0.011 t, respectively: Au: 3.183 kg, Ag: 7.7616 kg. Impurities (Pb, Sn, Zn, Fe): 4% - 0.44 t.

The process of electrolysis will result in the loss of certain metals, roughly 9%. The metal recovery in the electrolytic process will be: for Cu: 95%, for Ag: 97% and for Au: 98%.

After the electrolytic refining the following masses are obtained:

- 9.9275 t - 9.9 t of copper cathodes (as the final product)
- 550 kg of anode slime containing 275 kg of Cu, 7.529 kg of Ag and 3.12 kg of Cu.
- 270 kg impurities (Pb, Sn, Zn, and Fe) distributed in the anode slime and partly in the electrolyte.

After the electrolytic refinement of the anodes the obtained slime (550 kg) is to be set copper free to the copper content in the sludge of 2% for the further precious metals refining [9].

Refinement

Copper free anode sludge of 275.00 kg contains the following amount of precious metals:

- 3130.00 g Au
- 8215.00 g Ag
- 900.00 g Pd

With the following adopted recovery of precious metals (based on laboratory experiments): 99% for gold, 98% for silver and 96% for palladium the final products quantities per year are:

- 3100.00 g Au
- 8050.00 g Ag
- 860.00 g Pd [8, 9].

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**Fig. 2.** E-scrap processing and metal production technology block scheme [7]

**TECHNOLOGICAL PARAMETERS RELEVANT FOR ECONOMIC ANALYSIS**

**Pyrometallurgy**

Expected electronic waste quantity or PCBs to be processed is 16 t per year.

After the separation of metal and non metal part of the PCBs the metal part containing, 1.8 t of copper is subject of the pyrometallurgical process.
ECONOMIC ANALYSIS AND THE PROJECT EVALUATION

Market Analysis

In Serbia there is still no significant competition in the field of e-waste processing and metal production based on it. Only a few organizations have potential to be e-scraps recyclers. Finished products of this type have specific markets. Since the products are stock market subjects there are reputable and reliable buyers of these products. Established business links provide the right to believe that the main buyers of precious metals to be companies such as: Heraeus GMBH or Metalor Group Switzerland. The export mediator would be exporting company Jugotehna, Belgrade, Serbia.

The final calculation of the revenue was based on the planned selling prices of RBB – RTB Bor Company for Cu, Au and Ag [10] although the World Bank forecasts are a bit different [11]. For palladium value calculation the minimum current world market price is used [12, 13]. Thus the projected prices for the calculation of revenues are as follows: Cu - 4 600 €/t; Au - 24 000 €/kg; Ag - 360 €/kg and Pd - 12 000 €/kg. As far as the supply market is concerned the printed circuit boards, as the main raw material for this type of production, shall be procured through the existing collection centers in Serbia and the region. Procurement of normative materials will be performed mainly on the domestic market. The existing 10 kV substation would supply the production facility with electricity, water, fuel, oil and lubricants will be procured through appropriate services in accordance with the processing and production dynamics.

BASIC PARAMETERS

Production capacity, structure and value

- Copper: 10.260 t/year x 4600 €/t = 47196 €
- Gold: 3.100 kg/year x 24000 €/kg = 74400 €
- Silver: 8.050 kg/year x 360 €/kg = 2898 €
- Palladium: 0.860 kg/year x 12000 €/kg = 10750 €

Investments

Equipment 50200 €, Working capital 18290 € and Others 10642 €.

Funding

Own funds 31.49% or 24920 €; Bank loan for new equipment: 68.51% or 54212€

Capital costs

Depreciation 10%, Maintenance 5% and Insurance 0.5% of the equipment value, Interest 15%

Material and energy costs

Pyrometallurgy 4044 €, Electrolysis 7080 € and Refinement 3568 €.

Labor costs

Pyrometallurgy 5520 €, Electrolysis 14670 € and Refinement 9112 €.

Other expenses

Processing: Cu 700 €/t, Au 150 €/kg, Ag 10 €/kg, Pd 150 €/kg,

Environmental costs: 1000 €/year, Export supporting services 8% of Au and Ag income, Chemical analysis 1200 €/year, other expenses 2000 €/year.

Financial Projections and the Project Evaluation

All financial projections (Tables 2, 3, 4) for the six year period, including one year of investment and five years of production, indicate the project feasibility.

Table 2. Income Statement

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<td>Cumulative</td>
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Table 3. Financial cash flow

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Table 4. Economic cash flow

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- Income Statement indicates profit throughout the years of the production period
- Financial Cash Flow indicates permanent liquidity and continual positive net cash flows
- Economical Cash Flow indicates positive indicators of the project profitability:
  ✓ Internal rate of return IRR = 74.20%,
  ✓ Net present value (discounted at 15%) \( \text{NPV}_{15\%} = 138 \, 755 \, \text{€} \)
  ✓ Pay back period PBP = 2 years

Final evaluation of the investment in the project of e-scrap processing and metal production is completely positive. Based on the projected technology and basic parameters the project feasibility is out of question. Even with the more pessimistic basic parameters profitability of the project would be enviable and with significant ecological benefits.

CONCLUSION

The paper presents results of e-scrap processing and metal production project. The project is expected to be realised in the Mining and Metallurgy Institute Bor special production department within the medium term development plan.

The research results were the basis for the adopted technological solution described as one of the possible processing variants. Basing on the adopted processing technology and the production capacity the initial parameters for economic analysis were determined.

Economic analysis including short market analysis, the basic parameters and the financial projections (Income Statement, Financial Cash Flow and Economic Cash Flow) resulted with positive appraisal indicators. The analysis basic indicators, internal rate of return, net present value and payback period, approve the feasibility and profitability of the metal production based on e-scrap processing.

Beside the feasibility and the profitability the metal production based on e-scrap processing in Mining and Metallurgy Institute Bor is fully justified also from the environmental aspect. The project is expected to generate great economic and also ecological benefits not only for the investor but also for the Serbia and the Balkan region.

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REFERENCES

1. Ž. Kamberović, M. Korać, M. Ranitidović, Metalurgija-Journal of Metallurgy, 17 (3), 139, (2011)
10. www.rtb.co.rs