Abstract
The global demand for raw materials is increasing consistently in the modern world such that a resource efficient handling becomes more and more important in today’s manufacturing processes. Therefore, remanufacturing of degraded products and components is a major step within a sustainable manufacturing strategy. Remanufacturing planning has to consider heterogeneous raw material (used material), which has a direct impact on the refurbishing technology and the remanufacturing layout. This paper shows an analyzing concept regarding the planning of remanufacturing concepts to ensure reliable recycled products based on heterogeneous materials. The shown concept is substantiated with a case study “Recycling of lead anodes”. The evaluation of three concepts for the development of an automated process to recycle lead anodes, which were subjected to heavy wear during the electrowinning process of non-ferrous metals like copper, nickel or zinc, is in focus.

Keywords:
Efficient resource recovery, prevention of health effects, automated recycling process, planning remanufacturing.

1 INTRODUCTION
The production of metal is a starting point for the manufacture of almost every technical product or the construction of manufacturing plants. An important process step of the extractive metallurgy of non-ferrous metals like copper, nickel or zinc is the electrowinning process using electroplating with insoluble anodes. Thereby, the metal ions in the electrolyte solution are refined at the cathode due to electrochemical reduction [1]. The process of electrolysis is initiated by applying a decomposition voltage to separate the ions in the electrolyte [2]. The electrolysis process is sketched schematically in Figure 1.

State of the art is a manual process of resource recovery which contains three basic problems:
1. High energetic effort;
2. Health effects for employees;
3. Heterogeneous quality due to manual processing.

The main goals are the recovery of raw materials and the reuse of components to contribute to sustainable manufacturing. These raw materials and components are the base for secondary manufacturing of the lead anodes. Special attention has to be paid to the fact that recovered raw materials are not homogenous. Furthermore, post-processing of the recovered components might be necessary. It follows that production planning for secondary manufacturing requires different demands than production planning for primary manufacturing.

The development of an automated process ensures a reduced energy effort, an effective resource recovery as well as prevention of health effects for employees.

2 GOALS OF RESEARCH WORK
This paper focuses on the evaluation of the efficiency of three concept ideas to recycle lead anodes which have to be replaced because of electrochemical degradation. Three efficiency aspects were considered:
1. Expenditure of energy during the recycling process.
2. Development costs from concept idea to prototypic realization.
3. Effort regarding set-up times during the recycling process as well as maintenance.

To evaluate the expenditure of energy of each concept idea experimental setups on a model scale were developed. The development costs as well as the effort regarding set-up times and maintenance were estimated.

3 RECYCLING CONCEPTS
The lead anodes used in the electrowinning process consist of a hanger bar (copper bar which is shrouded with a lead sheathing) and a sheet. The development of an automated recycling process of lead anodes includes the separation of the lead sheathing and the copper bar. The goal is to reuse the copper bar in a remanufacturing cycle.
and to recycle the lead of the anodes for the manufacturing of new anodes. Therefore, three recycling concepts were developed to realize the separation of the different components of the anodes. The basic idea of each recycling concept is to utilize the different melting points of copper and lead. The melting point of copper is at 1085°C while lead liquefies at 330°C [3]. Heating the shrouded copper bar above 330°C causes separation of the components without effecting the copper bar. The concept ideas are briefly described below. A detailed introduction of the concept ideas is given by Rosebrock and Bracke [4].

3.1 Joule heating
The first concept idea is about heating the copper bar due to Joule heating. A flow of electricity through a conductor produces heat because of the electric resistance of the conductor [5]. If the electric current is sufficiently high, the temperature of the copper bar exceeds the melting temperature of the lead and a separation of the components of the anode can be realized. Furthermore, the copper bar will not be damaged such that it has not to be post processed before remanufacturing of the new anode.

3.2 Molten bath
The idea of the second concept is to plunge the coated copper bar in a bath of molten lead of the same alloy like the sheathing. After a certain dwell time the lead sheathing liquefies and gets separated from the copper bar.

3.3 Heating by induction
The third concept idea is to heat the coated copper bar by induction. Thereby an eddy current is induced in the lead sheathing to liquefy the lead [6].

4 ANALYSIS
The analysis of the concept ideas consists of four steps:
1. Evaluation regarding the expenditure of energy during the recycling process.
2. Evaluation of the development cost from concept idea to prototypic realization.
3. Evaluation of the effort regarding set-up times during the recycling process.
4. Comparison and evaluation of the concept ideas using data envelopment analysis (DEA).

Each recycling concept is evaluated regarding step 1 to 3. In step 4 the results of the first three steps are utilized to detect the most efficient recycling concept for the realization of a prototypic manufacturing process.

4.1 Joule heating
To estimate the expenditure of energy regarding Joule heating an experimental setup was developed in model scale as shown in Figure 2.

The samples were manufactured by shrouding copper wires (cross sectional area $A = 4\text{mm}^2$) with lead. The ratio of lead sheathing to copper was chosen to be equal to the ratio considering a hanger bar of an anode. Electric currents of 200A to 250A were applied to the shrouded wires while the time was measured until the lead sheathing gets separated. In addition the heating time for naked wires (with same cross sectional area) was measured for comparison purpose. The results of the experiments are shown in Figure 3. The electric current, which was applied to the copper wires, is shown on the x-axis while the corresponding time, until the temperature of the copper wire reaches the melting point of the lead is shown on the y-axis. Since the experiments were repeated several times for each applied electric current, the regression curves were fitted through the mean values of the resulting heating times using linear regression modelling [7] while the error bars indicate the range of the experimental results.

![Figure 3. Experimental results for separating the lead sheathing from a copper wire by Joule heating.](image)

It can be observed that the heating time decreases if the applied electric current is increased. Furthermore, it is shown that the heating time for the lead shrouded copper wires is much longer than the heating time for the naked wires.

The expenditure of energy for separating the lead sheathing from an anode’s copper bar can be estimated by upscaling the results. Therefore, the experimental results were compared to calculations done by using equations from theoretical physics. The heating time is equal to the ratio of the energy (given by the gradient of the temperature $\Delta T$, the mass $m$ and the specific heat capacity $c$) and the electric power $P$:[8]

$$\Delta t = \frac{\Delta T \cdot m \cdot c}{R \cdot I^2}$$  \hspace{1cm} (1)

The electrical resistance $R$ depends on the temperature such that it is increasing during Joule heating. The comparison of the analytical and the experimental results are shown in Figure 4. It can be seen that there is a small difference between the analytical and the experimental results regarding the heating time of the naked copper wire. This difference is caused by measurement errors as well as the fact, that the analytical equation covers ideal conditions.
The experimental results for the lead shrouded copper wire can be related to the analytical results. The problem is that the relation is only valid for the analyzed electric current range from 200A to 250A. Considering a hanger bar of an anode, the electric current has to be significantly higher to separate the lead sheathing from the copper bar. Therefore the upscaling can’t be done based on the electric current range. Instead, the experimental heating time can be related to the analytical heating time as shown in Figure 5.

The relation shown in Figure 5 is valid for the time range calculated using the analytical approach. The analytical equation provides the same heating times for a hanger bar of an anode if Equation 1 is scaled up proportionally. This can be done if Equation 1 is rearranged as shown in Equation 2.

\[ \Delta t = \frac{\Delta T \cdot \rho_{Cu} \cdot I \cdot A \cdot c}{\rho(T) \cdot I^2} = \frac{\Delta T \cdot \rho_{Cu} \cdot A^2 \cdot c}{\rho(T) \cdot I^2} \] (2)

Considering a hanger bar of an anode, the cross sectional area \( A \) increases compared to a copper wire. The temperature range \( \Delta T \), the density \( \rho_{Cu} \), the specific heat capacity \( c \) as well as the electrical resistivity \( \rho(T) \) stay constant such that the electric current \( I \) has to be increased proportionally to the cross sectional area \( A \). Since the ratio of the cross sectional areas is 125 (copper bar: \( A = 500\text{mm}^2 \), wire: \( A = 4\text{mm}^2 \)) the electric current has to be increased by the same factor leading to a range of electric currents from 25000A to 31250A. The expenditure of energy can be calculated by multiplying the electric power with the estimated heating time for a hanger bar. The most efficient operating point is visualized in Figure 6.

Applying an electric current of 29640A to a hanger bar of an anode leads to an expenditure of energy of 109Wh to separate the lead sheathing from the copper bar.

The concept idea of Joule heating is hard to realize in a full scale setup because a very high electric current has to be applied to a copper bar with a rather large cross sectional area. In addition, many hanger bars of anodes are designed such that only one ending of the copper bar is accessible. Without an additional process step of uncovering the contact surfaces on both endings, this concept idea can’t be applied to the majority of types of hanger bars. In case of hanger bars which’s both endings are accessible the development costs for a prototypic realization is estimated to be 50.000MU. The maintenance effort is predictably high because the contact areas, where the electric current is induced in the copper bar, have to be changed regularly due to damage caused by burning. The maintenance costs are estimated to be at 5.000MU per year.

The advantages of this concept idea are the low energy and development costs. In contrast, the maintenance costs as well as the applicability on a small fraction of types of anodes are the disadvantages of the concept idea.

### 4.2 Molten bath

The expenditure of energy regarding the concept idea of plunging coated copper bars in a bath with molten lead was estimated by developing a downscaled experimental setup shown in Figure 7.
The size of the bath was designed for bar segments. Therefore, the hanger bars were split into thirds and the segments were used as samples. The molten bath was set to two different temperature levels. Due to the fact that molten lead is not transparent, the samples had to be taken out of the bath after certain time intervals to analyze the separation progress. The dwell times until the lead sheathing was separated from the copper bar are shown in Table 1 for the two different temperatures of the molten lead. Furthermore, the temperature drop forced by the cold samples is displayed.

Table 1. Dwell times and temperature drop in molten bath.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Dwell time</th>
<th>Temperature drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>360°C</td>
<td>135s</td>
<td>5°C</td>
</tr>
<tr>
<td>380°C</td>
<td>90s</td>
<td>3°C</td>
</tr>
</tbody>
</table>

It becomes apparent that the lead temperature of 380°C is favorable because of two facts: The dwell time is shorter and the influence of the cold sample on the temperature of the molten lead is smaller such that the temperature drop can be compensated faster.

The expenditure of energy was examined by measuring the consumption of energy during the process of separating the lead sheathing from the copper bar for six samples. The temperature of the molten lead was set to 380°C. The cycle time for one sample was set to 3 minutes including the dwell time of 90 seconds and a regeneration time of another 90 seconds for compensating the temperature drop. An expenditure of energy of 2.5kWh was measured for 18 minutes and 6 samples. It follows that the expenditure of energy for a whole hanger bar can be estimated to be 1250Wh using the concept idea of plunging the hanger bar in molten lead.

For the realization of the concept idea of a molten bath in a prototypic setup, several tanks are needed to cover different lead alloys which have to be separated.

Therefore, the development costs are comparatively high and estimated to be at 150.000MU. In addition up to 26 heaters are used for every tank to melt the lead. In case of damage, these heaters have to be replaced during maintenance. The maintenance cost is estimated to be at 2.500MU each year.

The advantage of the concept idea is that this concept can be used for recycling all kinds of anodes. In contrast, high development, maintenance and energy costs are the disadvantages.

4.3 Heating by induction

The concept idea of separating the lead sheathing from the copper bar by inductive heating was analyzed regarding the expenditure of energy by using an experimental setup in full-scale. A medium frequency generator with maximum power of 40kW was used. The voltage was induced by a copper inductor with the frequency of approximately 12kHz. The inductor had a length of 980mm with 30 turns and an inner rectangular cross sectional area of 140mm x 85mm. The inductor is shown in Figure 7. The hanger bars were split into half and the segments were used as samples. In experiments different powers were applied while the energy and the time until the lead was separated from the copper bar were measured. The results are shown in Table 2.

Table 2. Experimental results for heating by induction.

<table>
<thead>
<tr>
<th>Power</th>
<th>Separation time</th>
<th>Energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>20kW</td>
<td>180s</td>
<td>0.7kWh</td>
</tr>
<tr>
<td>30kW</td>
<td>86s</td>
<td>0.7kWh</td>
</tr>
<tr>
<td>40kW</td>
<td>40s</td>
<td>0.5kWh</td>
</tr>
</tbody>
</table>

It can be observed that in case of the application of the maximum power the separation time as well as the expenditure of energy is the smallest. It follows that the expenditure of energy for a whole hanger bar can be estimated to be 1000Wh if the maximum power of 40kW is applied to the hanger bar using heating by induction.

The development costs are estimated to be at 120.000MU. The effort for maintenance as well as set-up times is predictively low and is estimated to be at 1.000MU.

The advantage of this concept idea is that the majority of different types of anodes can be recycled using this concept idea. The disadvantage of this concept idea is that the costs for development, maintenance and energy are rather high.

4.4 Data envelopment analysis

The efficiencies of each concept idea were compared relatively using data envelopment analysis (DEA). The DEA is a decision making tool to evaluate the relative efficiency of a set of comparable products, components, processes or process steps (Decision Making Units DMUs) and was published by Charnes et al. [9]. The efficiency is defined by calculating the ratio of a weighted sum of output parameters (benefits) and a weighted sum of input parameters (costs). Using linear programming the following equations are calculated iteratively with regard to the minimization of the efficiency θ and a vector of weighting factors λ for each DMU i:

\[
\min \theta, \lambda, s.t. \quad Y \cdot \lambda \geq y_i \quad (3)
\]
\[
X \cdot \lambda \leq \theta \cdot x_i \quad (4)
\]

Considering a number of N decision making units using K input and M output parameters, the vectors x and y denote the input and output vectors of DMU i. The input matrix K×N for all DMU’s is denoted by X while the output matrix M×N for all DMU’s is denoted by Y. Several applications can be found in literature [10].

The efficiencies of the concept ideas were analyzed with regard to different input and output parameters as shown in Table 3.

Table 3. Input and output parameters for DEA.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Output parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development costs</td>
<td>Universal usability</td>
</tr>
<tr>
<td>Expected costs per year</td>
<td></td>
</tr>
</tbody>
</table>

The development costs imply the effort for construction and development from the experimental setup to prototypic realization. These costs were estimated for each concept idea as mentioned before and are shown in Table 4.
The development of an automated process and the effects for employees have to be reduced to a minimum. In addition, health optimized recovery of raw material as well as the reuse of the experiments. The universal usability is 90%. The requirements for enabling a secondary production are an optimized rate. Considering the geometry of the copper bars, the majority usability of 100%.

The concept idea of using a molten bath has a universal secondary production of lead anodes used in the electrowinning process of non-ferrous metals. The goal of this study was to establish a basis for the recycling process or preparing the shrouded copper bars itself. Considering the concept idea of Joule heating the fraction of anodes which copper bars are accessible from both endings is approximately 10%. For about 90% of anodes, a further process step is needed to uncover the second ending.

The anodes are manufactured using 4 different lead alloys. The development of the concept idea of plunging the hanger bars in molten lead includes the manufacturing of 4 tanks to cover the different alloys. Therefore, the concept idea of using a molten bath has a universal usability of 100%.

Considering the geometry of the copper bars, the majority of hanger bars can be covered with the inductor used in the experiments. The universal usability is 90%. The universal usability factors are summarized in Table 6.

Table 6. Universal usability of each concept idea.

<table>
<thead>
<tr>
<th>Concept idea</th>
<th>Universal usability factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joule heating</td>
<td>0,1</td>
</tr>
<tr>
<td>Molten bath</td>
<td>1</td>
</tr>
<tr>
<td>Heating by induction</td>
<td>0,9</td>
</tr>
</tbody>
</table>

The result of the data envelopment analysis is shown in Table 7.

Table 7. Results of the DEA.

<table>
<thead>
<tr>
<th>Concept idea</th>
<th>Relative efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joule heating</td>
<td>0,267</td>
</tr>
<tr>
<td>Molten bath</td>
<td>0,889</td>
</tr>
<tr>
<td>Heating by induction</td>
<td>1</td>
</tr>
</tbody>
</table>

It can be observed that the concept idea of heating by induction shows the highest efficiency considering the parameters of development costs and costs per year as well as a universal usability factor. Although the expenditure of energy in case of the concept idea of Joule heating was the lowest, the efficiency was not the highest because of a very low universal usability factor.

6 OUTLOOK

The analysis in the presented study bases on parameters regarding development, maintenance and energy cost as well as the universal usability. These parameters were estimated for each concept idea. Since the results of this study base on estimations, further analysis is necessary to proof the results. In addition other parameters could be taken into account to increase the accuracy for selecting the most efficient concept idea.

In the following step the development of a full-scale prototype has to be realized. Besides the requirements for an optimized recovery of raw material, a maximized reuse of the copper bar as well as a minimization of health effects for employees, the recycled anodes have to show the same performance like anodes manufactured in primary production. First approaches to analyze and to compare the performances were published by Rosebrock and Bracke modelling the failure of anodes in the electrowinning process of non-ferrous metals using time series analysis [11,12]. Additional methods to analyze the reliability of the anodes will be applied, e.g. the comparison of failure rates regarding their classification in early failures, random failures as well as wearout failures [13].

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8 REFERENCES


