WEEE Recycling at IME – RWTH Aachen: From Basic Metal Recovery to Resource Efficiency

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1 Introduction

The WEEE directive 2002/86/EG defined WEEE as the end-of-life products from electrical and electronic equipment (EEE) [1]. Waste from electrical and electronic equipment is one of the fastest growing wastes in Europe (3 to 5 % per year) and it is expected to be increased to 12.3 mill. t by 2020 [2, 3]. According to estimates, at least 20 to 50 mill. t of electrical and electronic equipment are produced annually worldwide [4]. WEEE can be defined as a complex mixture of different materials and components with important presence of hazardous substances, which demands proper management to avoid environmental and health problems. In addition, it is estimated that an important amount of resources (e.g. 10 % of the gold production, https://ec.europa.eu/environment/waste/weee/index_en.htm) are spent in the fabrication of electronic equipment. Therefore, it is not only the considerable amount of scraps to be processed but also the importance of developing an effective handling in terms of recovery of valuable metals that provide us the possibility of increasing the resource and economical sustainability of the recycling process. In this context, the IME – Institute for Metallurgical Process Technology and Metal Recycling at RWTH Aachen has set itself the goal of developing a process concept in which most of strategic metals from the spent electronic equipment can be recovered efficiently and in an environmentally friendly manner. This processing involves different areas in need for innovation like preprocessing, hydro- and pyrometallurgical treatment. It is worth mentioning that developments in WEEE recycling face some challenges that needs to be addressed with special attention, like the high inhomogeneity of the electronic waste, the variety of elements and the nature of containing materials, as in some cases valuable metals can be found distributed in diverse materials like shredding dust, metals, plastics, glass, ceramics and production wastes. In addition, organic containing materials release a large amount of heat during combustion, and in cases like plastics, they can contain a significant amount of halogenated flame retardants, which promote the formation of corrosive gases at high temperature and limits the capacity of the exhaust gas systems.

The IME institute, together with key industrial players and supported by several public funding entities, has tried to tackle the major challenges in the electronic waste recycling sector for over 15 years, to bring the system towards its sustainability and to supports the circular economy of metals in a semi cradle to cradle structure with near-zero wastes. In 2017, an article with the title “Sustainable electronic scrap recycling through individual process design” [5] was published to show some preliminary results of the ongoing activities on WEEE Recycling at IME. This article intents to highlight the accomplished results and show some of main progress since our last publication and update the future prospective in the research on WEEE Recycling at our institution. For detailed information about projects on WEEE recycling you can also visit our website (www.ime-aachen.de).

2 Research activities in WEEE recycling at IME

To supporting a circular view of electrical and electronic equipment, it takes several stages from collection of end-of-life EEE to production of “new” materials from secondary raw sources. After collection, a strategic classification takes place according to WEEE regulations, through which ten categories had been defined up to 2019 [6]:

1. large household appliances,
2. small household appliances,
3. IT and telecommunications equipment,
4. consumer equipment and photovoltaic panels,
5. lighting equipment,
6. electrical and electronic tools (with the exception of large-scale stationary industrial tools),
7. toys, leisure and sports equipment,
8. medical devices (with the exception of all implanted and infected products),
9. monitoring and control instruments,
10. automatic dispensers.

The categories are selected according to parameters like content of hazardous substances, valuable materials and amount of effort for its processing. Following the classification, the preprocessing of electronic scrap takes places before any metallurgical treatment can be done to extract metals from it. Therefore, the preprocessing is after collection probably the most challenging stage, as it needs to be done in such a way that the amount of valuable re-

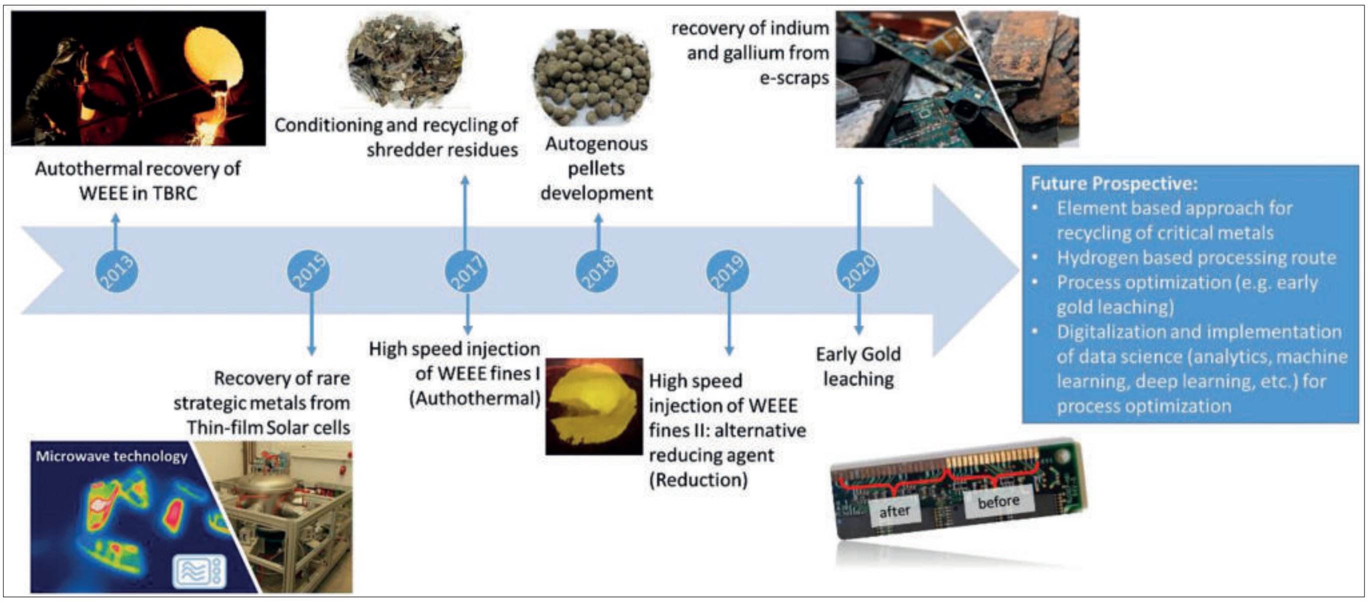

Fig. 1: Timeline on WEEE Recycling at IME until 2020 and future perspective

sources that is being concentrated compensate the amount of energy required. In addition, the amount of material that can be lost during the sorting processes needs to be considered. After preconditioning, material fractions (e.g. ferrous, non-ferrous, low magnetic materials, special parts, shredder fractions) are ready for further metallurgical extraction processes. Research activities at IME cover the technical spectrum from preconditioning to metallurgical processing by e.g. early gold extraction, autothermal recovery of valuable metals (e.g. Cu, Au, Ag, Sn, Pb, …), conditioning and process design for complex organic containing materials like shredder light fraction (SLF), mobile phones, thin-film solar cells and selective extraction of strategic elements like gallium and indium. Figure 1 describes the main timeline of our research activities, from our first WEEE project, the development of an autothermal recovery process, to our current research. In the diagram, our important achievements over the years can be seen, from the preconditioning towards efficient metal recovery to remediation strategies for critical “wastes” in the WEEE recycling. Today, we have completed a strong baseline in this research area and are ready to point out future developments in topics like designing of an element-based recycling approach where critical metals can be recovered, as well as moving towards generation and strategic utilization of hydrogen in the processing route of WEEE to minimized CO_2 foot print and process optimization to reach cleaner technologies with minimized material losses and increased sustainability.

2.1 Preconditioning of WEEE

The preconditioning of WEEE can divided into two main categories. On the one hand, the mechanical preprocessing, where the material is crushed down into small particles and sorted according to material’s properties like density, magnetic properties and conductivity [3, 7]. From the mechanical preconditioning some products are obtained e.g. Fe-fraction, Non-ferrous fraction, PCBs, shredder light fraction (SLF), manually sorted units (Mobile phones, loud speakers, batteries, etc.). On the other hand, the thermal preconditioning, where the material is subjected to higher temperatures and under some atmospheric conditions to promote reactions, degradations, or volatilization of metals. Some of these processes are e.g. pyrolysis, gasification and combustion. From the thermal preconditioning solid-product, permanent and condensable gases are produced, which quality depends strongly on the chosen technology and process parameters like heating rate, temperature, process time, cooling rate, etc. Generally speaking, there is no unique way to arrange a process structure but rather a combination of process steps which makes the process optimal within the acceptance of reasonable metals losses and energy requirement.

IME has worked in closed cooperation with leading institutes in the field of mechanical preprocessing in Germany, allowing the multidisciplinary development of different process concepts and using cutting edge technology in process steps like shredding, sieving, magnetic separation, eddy-current separation, sensor-based sorting and others. Although mechanical preprocessing has been greatly developed in the past decade, the production of wastes like shredder light fractions (SLF) and dust has reached considerable amount of material, which rounds the 2.5 billion tonnes per year only in Europe (including processing of other metal containing materials at the end-of-life like automobiles and WEEE) [8]. It is important to notice that, even if these are considered as waste, some metals are still concentrated in weight per cent like copper (2.74 %), tin (0.05 %), lead (1.05 %), zinc (0.33 %), and some precious metals like silver (119.4 ppm) and gold (13.8 ppm). These “wastes” represent a big cost for the industry as it is forbidden to dispose of them in landfills, and thus necessitate to pay for energy recovery in incineration plants, where valuable metals are lost. In addition, other limitations of the mechanical processing of WEEE can be noted, such as unsuccessful mechanical separation of strategic elements

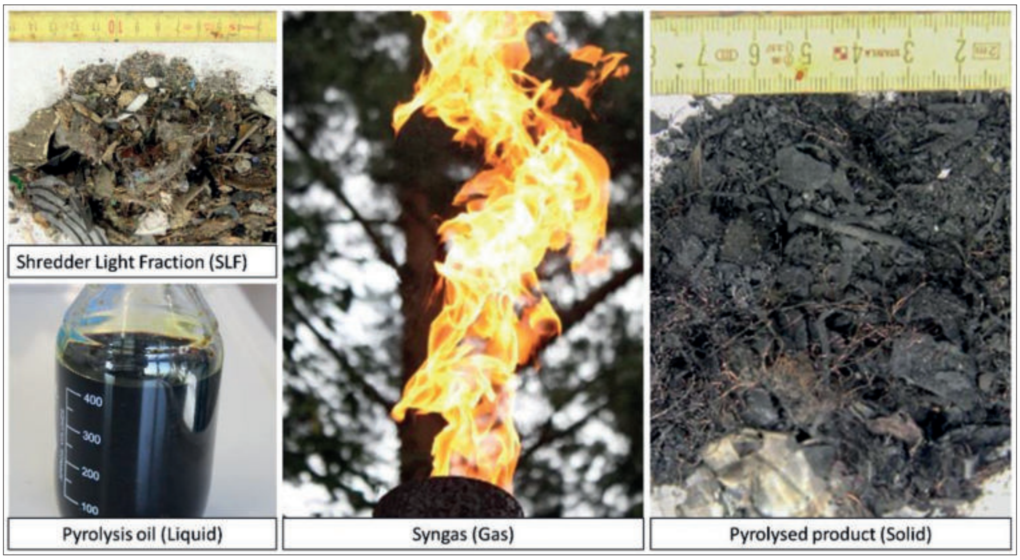

Fig. 2:
Shredder light fraction and main pyrolysis products after treatment pyrolysis oil, syngas and pyrolyzed solid product

like e.g. gallium and indium. Therefore, the implementation of thermal techniques in addition to mechanical processing appears to be a good opportunity, as is the case of pyrolysis.

Thermal conditioning of metal containing organic wastes e.g. printed circuit boards PCBs, SLF, mobile phones, solar panels, and others, is an area where IME has been active for some years. Our main results show a technology with good potential for deep cleaning of wastes in terms of halogens, selective volatilization of strategic elements e.g. gallium, Indium and antimony, control of intrinsic heat, production of flammable gases, hydrogen production, powder reducing coke and solid products with improved mechanical properties for an eventual metal separation. This research compile key information regarding the degradation mechanisms of organics during the pyrolysis of WEEE, the characterization of pyrolysed products, the analysis of metallurgical applications for pyrolysed chars as alternative energy source in autothermic smelting of WEEE and the valorisation of its potential use as reducing agent in the copper industry and an holistic approach for recovery of strategic elements. Experiments have gathered information from laboratory scale trials in grams to demo scale trials using a Top Blown Rotary Converter (TBRC).

In the research performed on Shredder Light Fraction from WEEE some highlights can be noted. In Figure 2 the main spectrum of products is indicated as pyrolysis oil, syngas and pyrolyzed solids. As it can be seen, the degradation process turns the complex waste made out of diverse type of material (foam, textiles, rubbers, dust, wood, metal wires, electronic components, metal foils, etc.) into a more homogeneous and brittle product, where no oxidation of metals takes place and organics are transformed into a pyrolyzed coke. Valuable elements in metallic and oxide form experience an upgrading effect for e.g. Si, Al, Ca, Cu, Pb, Fe, etc., while the material undergoes a weight reduction up to 50 %. This improves the net charging capacity of this material in any melting unit with an important minimization of the off gas due to up to 80 % reduction in the concentration of halogens. The pyrolysis process also delivers, if driven under good conditions, a syngas containing CH_4 (23 vol. %), H_2 (24 vol. %), CO (18 vol. %), ethylene, ethane and others. This results in an heating value estimated at around 48.6 MJ/kg, which gives to this syngas a strong potential as energy source or even as reducing gas in any metallurgical reduction process. In addition to syngas, the pyrolysis oil, which represent all the condensable hydrocarbons, was found to be a combination of three main constituents: paraffins, naphthenes and aromatics, resulting in a heat calorific value of up to 26.3 MJ/kg with also a good potential as fuel. The pyrolysis oil can gather an important amount of volatized halogens from WEEE during pyrolysis, which makes refining and cleaning of such an oil an expensive and challenging procedure.

Nevertheless, it could also be observed that production of oils during pyrolysis can be reduced by promoting catalytic degradations either in the solid material or in the gas generated during the pyrolysis process. This could give an advantage as more syngas with higher concentration of hydrogen can be produced while production of oil is minimized. More details about this research performed at IME, which includes upscaling of the pyrolysis process and deep analysis of the metallurgical potential of pyrolysis products can be found in the dissertation “Process concept based on pyrolysis for integration of Shredder light fractions (SLF) in the Recycling of Waste Electrical and Electronic Equipment (WEEE)” [9].

A thermal conditioning could also offer other advantages as a method for strategic element’s separation. At IME, a project that focusses on a holistic recovery of indium and gallium from smartphones was conducted. Following the comminution in an impact mill, crushed devices are processed in a pyrolysis step in order to remove the organic fraction (plastics). Thermal treatment enables separation of indium via halogenation and volatilization. During the thermal decomposition of plastics, HBr is formed in order to act as halogenation agent so that no additive halide containing material is required. After pyrolysis, gallium arsenide still remains in the solid residue and can be further concentrated in a fine fraction by use of grinding and sieving. Subsequently, gallium is extracted selectively by alkaline oxidative pressure leaching using sodium hydroxide and gaseous oxygen. Other valuable metals such as gold, silver, tantalum and rare earth element are neither affected by pyrolysis, nor by leaching and can be recovered from the leach residue. Other details about this work can be found in the dissertation "Development of a process concept for recovery of indium and gallium from electronic scrap", which is expected to be published in 2020.

A similar research direction was the study performed on thin-fill photovoltaic modules for recovery of cadmium telluride (CdTe) and copper, -indium, -gallium (di)selenide (CIGS), which are critical materials in terms of vulnerability and supply risk. This research was performed using preconditioning with microwaves under inert atmosphere in a microwave pyrolysis process. Microwaves are largely reflected on the surface by conductors with free electrons. However, if the surface to volume (O/V) ratio is very high, as is the case with metal foils or surfaces coated with conductive layers, significant excitation of the electrons on the surface can occur. The heat generated in this way cannot be dissipated sufficiently due to the small volume, therefore the temperature in the material rises. Since thin-film panels consist of (semi) conductive layers that are vapor-deposited onto a substrate glass, the recycling of thin-film solar panels is a promising area of application for microwave technology. Experiments on microwave pyrolysis covered different parameters in terms of atmosphere (air, protective gas, vacuum), exposition time and power supply. The investigations carried out for this technology have shown that, in principle, a distillation of the semiconductor layers by means of microwaves is possible in the case of CdTe modules. In the case of CIGS modules, only complete removal of the selenium was observed. The CIGS layer is indirectly heated by the conductive molybdenum, which then oxidizes and volatilizes. In addition, when a critical temperature (approx. 600 °C) is reached, the substrate glass becomes the microwave receptor, which consequently leads to the glass melting and the valuable metals being lost in this way, as they remain in the glass material. Further details about this research can be found in the dissertation "Microwave treatment of CdTe and Cu(In, Ga)Se_2 photovoltaic scrap" [10].

2.2 Metal recovery from WEEE

Metallurgical recovery takes place once the metal concentration in the material stream has been increased and critical hazardous material has been removed during the preconditioning steps. There are in general two main types of metallurgical processing that can been applied to WEEE streams: pyrometallurgical and hydrometallurgical processes. Similar to preprocessing, the general structure of metallurgical recycling of WEEE is no unique and is made of different steps where pyrometallurgical and hydrometallurgical techniques are combined in order to reach out each target elements. The pyrometallurgical treatment of WEEE scraps can be mainly distributed into two recycling units: the TSL (AUS/ISA) smelter and the so-called "Kaldo furnace" or "Top Blown Rotary Converter, TBRC". The first one is probably the most commonly used smelting unit in Europe, whereas the second one, is not only used industrially in Boliden, but also have a special research interest at IME-RWTH University in Aachen due to its enormous flexibility in terms of input material (e.g. 100 % WEEE input with the TBRC compared to max. 10 to 14 % in the TSL [11, 12]) but also in the simplicity of the operation, space requirement, lower investment costs as well as relatively shorter maintenance.

The metal recovery research on WEEE Recycling at IME can be also divided into two areas. On the one hand, we have developed an Autothermic smelting process for WEEE, where three different concepts of operation have been evaluated for different material streams: Continuous charging, injection of pulverized organic containing material and pelletizing of shredder dusts. On the other hand, we have also intensively worked on alternative processing using non-cyanided compounds for early gold leaching process.

2.2.1 Autothermal smelting of WEEE

All pyrometallurgical treatment of WEEE have in common the need of an energy source to reach high temperatures, turbulences to increase the slag-metal interaction, good settling of the metal phase for good slag-metal separation, good slag properties to increase the process efficiency and casting behavior. A melting unit should fulfill these requirements in order to obtain a good process efficiency and a high metal yield. The Top Blown Rotary Converter (TBRC) offers, besides the previous requirements, an enormous process flexibility in terms of variety of input material and good process control. The TBRC consists of a furnace with a vessel in the form of a rotating cylinder, which is heated by an oxygen-oil-gas burner. The TBRC Unit at IME has a capacity of 0.5 m^3 melt volume and can reach a temperature up to 1550 °C with an oxy-fuel operation burner. For electronic scrap recycling, the average temperature needed is 1300 °C. As it is shown in Figure 3, our plant has a state-of-the-art exhaust cleaning system with a quenching box, an electrostatic filter, alkaline scrubber and fabric filter.

Electronic scrap is especially interesting for its latent heat, which is released during smelting by supply of oxygen. The process can be operated in such a way that the smelting process can be performed with only the supplied latent heat in the material. This process is called autothermal smelting. This minimizes the energy required to melt the metals which are present in the feeding material [13]. In the modern WEEE recycling history at IME, the development of an environmentally friendly process capable of treating up to 100 % WEEE scraps in the input material using injected oxygen for the full combustion of organics and near-zero consumption of conventional fossil fuels, was probably the first step of many in this field starting in 2009. For this process, different material streams were tested and in all cases the combustion of organics under relatively controlled condition was successful. Process efficiency reached up to 97 % and demonstrated that the concept of organic being used for their self-smelting process

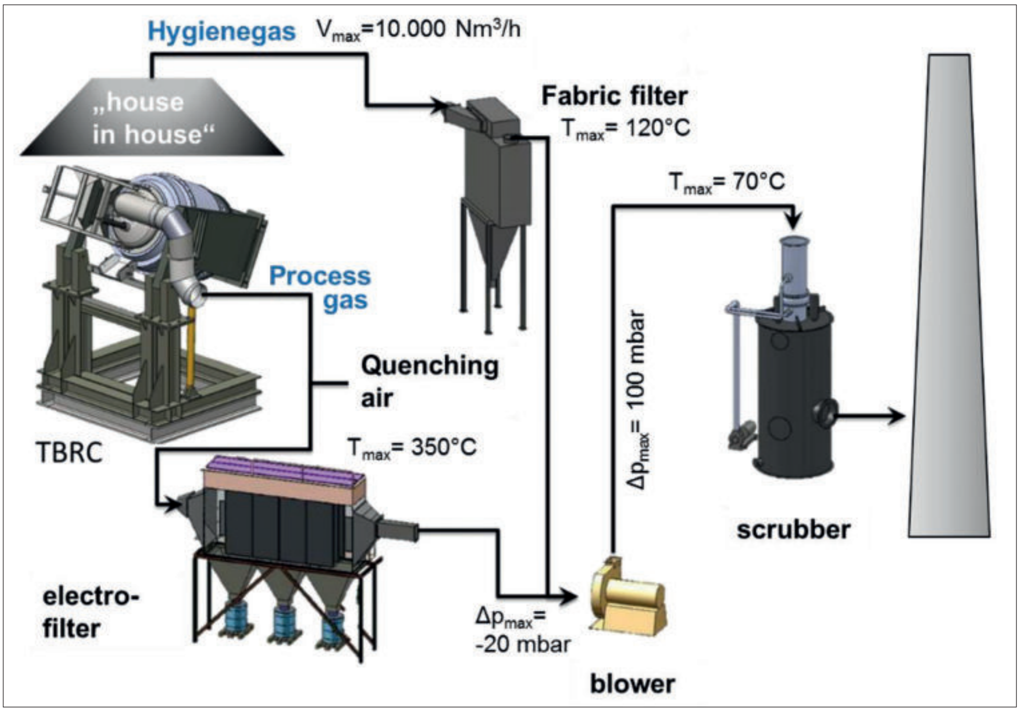

Fig. 3: Offgas cleaning system for the pilot scale TBRC at IME-RWTH Aachen

can be guaranteed. The details of this development have been published in the dissertation „Autothermal recovery of valuable metals from electronic scrap in the TBRC" [14]. Despite the good performance of the process, there are still some challenges to be faced during operation, like providing the correct supply of oxygen when the material's composition is not constant. Not achieving this control could lead to undesired oxidation of copper and thus delays in the process due to unnecessary reduction stages to recover the metal and to clean the produced slags. In addition, the process face some challenges for materials with low density (like SLF) and low concentration of metals, which leads to the vast production of exhaust gas; for extremely low particle size (e.g. shredder dusts) due to undesired clogging of the feeders and for premature suction of unprocessed particles from the furnace due to the high turbulence in the smelting. Research has been conducted at IME trying to find the solution to such challenges.

2.2.2 Charging technologies: high speed injection and pelletizing of strategic WEEE streams

Powders and dusts from WEEE are a valuable source for different metals like copper or precious metals e.g. gold and silver. Besides this, they also contain large amount of organics, ceramics and oxides, which ultimately affect the smelting process. Our research on the metallurgical effects of these fractions and towards a process solution was based on two different operation principles: high speed injection and pelletizing technologies. In both cases, the material is fed into a molten slag bath. Within this research, the influences on the slag phase are simulated using the thermochemical software FactSage™, and the material-specific oxygen amount required to combust the organic constituents is calculated. The results are tested and optimized in preliminary laboratory-scale experiments and then scaled up to technical size in our TBRC. From the observed results, it is still premature to conclude which technologies can be accepted as the "best", since both of them offer advantages and require additional work for optimization. Nevertheless, we have gained several insights about a potential industrialization through successful demonstration scale experiments. In Table 1 the high-speed injection and pelletizing technologies are compared to conventional charging via vibration feeders in the autothermal smelting of WEEE. The high injection of shredder dust offers an increased turbulence for a rapid processing and better process control, which allows an increased performance of the material as fuel. If the injection is performed under controlled conditions, it is possible to modify the operation conditions from oxidizing to reducing, which could lead to the reduction of the copper contained in the slag and a better control of the melt temperature. Pelletizing leads to a stable process with low flying dust production, due to the good mechanical properties of the input material as well as the decreased turbulence in the furnace. Therefore, pelletizing allows for a controlled combustion and low material losses. Nevertheless, the energy and materials (binders) required add an extra cost to the process. It is worth mentioning that pelletizing could allow the addition of fluxes directly mixed to the input material into the melt, and thus

Table 1: Comparison of the tested technologies to incorporate organic containing metals from WEEE in an autothermal smelting process

Criteria	High speed injection	Pelletizing	Vibration feeder
Stability	++	+++	+
Turbulence	+++	+	+++
Efficiency	++	++	+
Relative costs	++	+++	+
Process control	+++	++	+

help reach the desired process window for optimal performance and process control. Generally speaking, both injection and pelletizing offer much better performance for the recycling than vibration feeders, which has poor stability, process control and low efficiency.

As a part of the research with high speed injection technologies, the injection of pyrolyzed cokes fines in molten slags was studied, with the aim of recovering copper from copper containing slags. Pyrolyzed cokes fines can be obtained directly after pyrolysis of e.g. SLF from WEEE at the solid product without any additional treatment. This material has a particle size of <1 mm (to even <90 µm) and exhibits low density, making this impossible to agglomerate without binders and difficult to charge directly while avoiding undesired material suction from the melting unit. For these reasons, high speed injection technologies appear as a perfect solution when dealing with pyrolyzed cokes. Results from the demo scale trial indicated that copper reduction reached the highest efficiency if this material is injected inside the molten slag with the oxy-fuel burner running under reducing conditions ($\lambda \sim 0.7$). The process offers high reduction efficiency and fast reaction time, with the biggest advantage of offering good slag-solid interaction between the molten slag and the reducing agent. It could also be evidenced that remaining hydrogen contained in the organic chain in the pyrolysed coke can be liberated during the smelting supporting the reduction process. This effect could help decresing the CO_2 footprint of the process by using hydrogen as an alternative reducing agent, if compared with common solid fossil reducing coke where only carbon is used for the reduction [9].

2.2.3 Early gold leaching

Gold is mainly used as galvanized layers in electronics as a measure against surface corrosion. Despite its low concentration, gold represents the metal with the highest value in electronic scrap and the one almost "everybody" is most interested. Although the state of the art enables almost complete metallurgical recovery of gold and other precious metals, it also has major disadvantages. On the one hand, it requires complex mechanical comminution and sorting, which causes golden layers to be split and distributed in different fractions, which causes a dramatic reduced yield of up to 25 % in the entiry recycling process. Another important disadvantage is the length of the process as it takes several weeks until the gold can be separated and recovered. As the primary value carrier, this requires enormous capital commitment.

Hydrometallurgical processes are particularly suitable due to their high selectivity and enable efficient gold recovery. Thiosulfate is the most promising and environmentally friendly leaching agent to support an non-cianide recovery route, but it also shows the major disadvantage of being required in a high amounts. With optimized parameters, an almost complete and highly selective recovery of gold can be made possible within 24 hours, while other metals of lower value remain in the residue.

3 IME's perspective on the future of WEEE recycling

Despite major developments in the different steps needed for WEEE recycling, there are still major challenges for WEEE recycling. In order to move towards a greener and more sustainable economy, the current concept for WEEE recycling shows its limitation: by focusing on the recovery of base metals through the copper route, some critical and strategic metals are lost to the slag. Moreover, even if a fully autothermal recycling process would be implemented globally for WEEE recycling, it is still only an energy recovery of the organic content of the material, far from a potential upcycling. The increasing complexity of the different WEEE streams also requires more robust and reac-

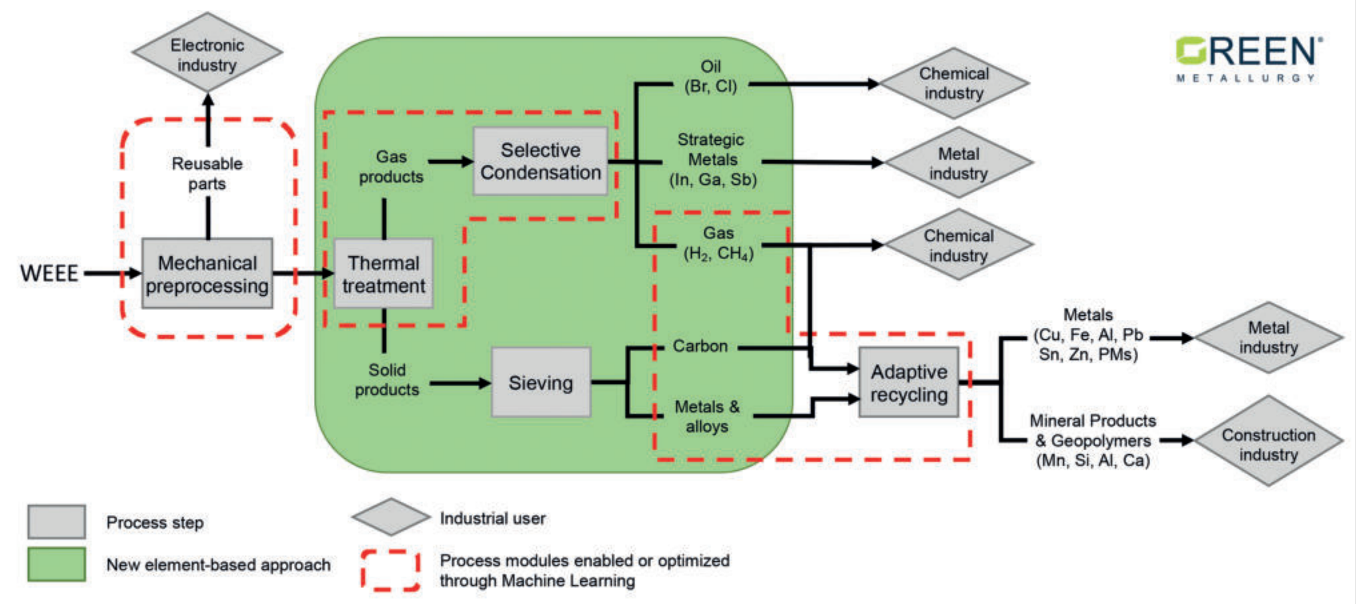

Fig. 4: IME's concept for future WEEE recycling integrating an element-based approach and process optimization through automatization and machine learning

tive process, with faster analysis and decision making. From these two main challenges naturally derives the future direction of our research: moving from a base metal recovery process to an element based process, trying to valorize WEEE at an elemental level (carbon, hydrogen, metal), and the automatization and digitalization of WEEE recycling, using current development in machine learning to enable fast and reactive processes. By broadening the element-based approach into a fully integrated process using achievement in the domain of machine learning and automatization, as seen in Figure 4, the ressource and energy efficiency of WEEE recycling would be greatly increased, as a first step towards a sustainable WEEE management.

3.1 New element-based approach to WEEE recycling

In both incineration of fine WEEE fractions and metallurgical recycling of WEEE, focus is placed on the recovery of metal and organic are considered an energy source at best, or undesired at worst. But to enable a greener process, the combustion of the organics present in WEEE cannot be the final step, as these are complex hydrocarbons chains, which needed a lot of energy and material to be created. A balance has to be found between the use of organics for the energy needed for the process, and a more thorough preconditioning to allow at least partial upcycling of the elements. In essence, WEEE are composed of carbon, hydrogen and metals/alloys. An improvement in mechanical pretreatment through innovative sensor technologies would allow early removal of usable components, but there are currently no viable technologies to minimize the loss of the organics on a printed circuits board. An alternative to simple energy conversion could be found in the use of pyrolysis technology as a thermal pretreatment. By submitting WEEE fraction with high organic content to a pyrolysis, it is possible through optimized catalytic reaction approach, if not reach, the separation of carbon, hydrogen and metals.

The cracking of hydrocarbons under catalytic pyrolysis produces a clean and highly calorific gas composed of hydrogen and small chain compounds (e.g. methane). As these gases are non-condensable at normal pressure and room temperature, they are easily recovered and separated from other toxic volatile compounds (like bromine or chlorine) which can be then collected in a condensed concentrated oil. Carbon and metal are found in the solid products of the pyrolysis, but as carbon is found in fine size and metal in coarse size, a relatively easy sieving allows for the separation of these fraction. Doing these steps would allow for a more element oriented approach to recycling: metal can be recovered in optimized smelting process, carbon can be use directly as a reducing agent and hydrogen/methane can be used either as an alternative and greener reducing agent or as a primary chemical compound for the production of new materials. Such approach to WEEE recycling is also only possible through better modelization and optimization of the recycling process and requires better analysis and faster decision making for an efficient industrialization.

3.2 Process optimization through automatization and machine learning

Metallurgical WEEE recycling is a complex process. As indicated in the metal recovery section, regardless of the chosen process steps, there is still an important room for optimization. For instance, in the autothermal smelting of WEEE, the supply of oxygen should be controlled by and adapted to the organic amount that is being injected or charged to the melting unit, which is also influenced by other parameters like suction power, temperature, melt volume, quality of exhaust gas. The system should be robust and accurate enough so that oxygen is supplied only in the amount required to burn off the organic, while avoiding oxidation of copper, cooling in the melt or even overheating. Unproper treatment leads to decreased metal yield and increases the general operation costs. In hydrometallurgical processing, metals are being dissolved and extracted from the solutions by manipulating the pH and additives, for example in neutralization process, or by supplying electricity in an electrowinning process. The pH and energy supply should be adjusted according to the accompanying elements and temperature, while avoiding undesired precipitation and/or contamination of products with impurities and passivation of electrodes. In the field of metallurgy, these steps are still done, in most cases, by manual handling of data, which makes such adjustments challenging for a process that is constantly changing due to the high heterogeneity of the feeding material.

Current developments are driving the technology to a point where systems (modules) should be able to process data immediately, communicate with other modules and rapidly elaborate local changes in the process if there are changes in the feeding materials or in the quality of the product [15]. This is the core of the so-called Industry 4.0: here, models and algorithms are created with the help of machine learning (ML) algorithms to process data and quickly execute control actions. The application of ML methods to chemical processes should enable the creation of optimized systems that can learn from their functionality and improve their performance in real time. For this purpose, IME is launching its research area in automatization and digitalization for process metallurgy with projects in the WEEE recycling and lithium-ion battery sectors. In this research, our goal is to get in touch with such a development in data science and to follow a strategic approach towards this digitalization. This involves an early stage on data mining, digitalization and online measurements, data transferring & storage, pre-processing of process data, and development of basic elements that can help us perform a new set of metallurgical process analysis like data visualization of multidimensional systems, evaluation, regressions, and others. After clarifying and settling of the process digitalization and creation of robust data mining, further development can be implemented in the direction of machine learning, deep learning, and neural networks, which can help us to create algorithm that can assist the operators to perform predictions on the process performance and to take part in the decision making. This work can not be performed alone. Therefore, the seek for strategic partners and industrial stakeholders will be necessary to get access to real Big Data, as well as to update the current technology at our institution for process demonstrations in a near-industry scenario. This will allow IME and its partners to move towards more circular and adaptive metallurgical process, especially for complex material streams. A first step for the "Recycling 4.0".

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