JOM, Vol. 69, No. 3, 2017
DOI: 10.1007/s11837-017-2283-0


# Germany's Research Platform for Sustainable Process Metallurgy

## *From Nano to Mega Scale Experiments*

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Figure 1. Hot wall induction furnace at the Institute for Process Metallurgy and Metal Recycling (IME).

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## Background

Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University was founded in 1870 and, in 2007, was selected by the German Research Foundation as one of nine German Universities of Excellence. Advancement of non-ferrous metallurgy is the focus of the Institute for Process Metallurgy and Metal Recycling (IME) at RWTH. IME is financed in equal parts by state, industry, and public funding.

A key competency of IME is the continuous development of economic and resource-efficient processes for the treatment and revaluation of raw materials and wastes. Solutions need to be innovative, competitive, apply to industry's needs, and fulfill strict requirements for sustainability and zero-emission metallurgy. Work starts with thermochemical modeling and theoretical studies, as well as fundamental research, and extends to experimental large-scale test runs. IME facilities measure more than 1500 m², with the capacity to support research work on all metals. Generated off-gases are treated centrally in electrostatic gas and fabric filters and scrubbers, with online measurements enabling compliance with the government's strict environmental regulations. IME also houses a certified analytical lab, which offers service through a wide variety of organizations.

## IME Research Departments

IME's research is organized within five main areas to cover a broad range of proven, innovative metallurgical process

Figure 2. IME's leaching and precipitation cascade line enables recovery of rare earth elements or nickel from >100 kg/d ore.

technologies such as recycling-, slag-, vacuum-, hydro-, microwave-, electro-, aluminothermic- and nanometallurgy.

***Pyrometallurgy*** focuses on the treatment of diverse primary and secondary materials such as WEEE (waste electric and electronic equipment), red mud, used hydrogen storages, spent catalysts and batteries, UBCs (used beverage cans), grinding debris, and more. IME's workshop area supports a wide-ranging repertoire of furnaces and aggregates in order to extract the desired metals and separate them from accompanying elements. Alongside various hot wall (Figure 1) and cold wall VIM (vacuum induction melting) furnaces up to the capacity of 100 L, the IME portfolio offers a large variety of pyrolysis furnaces and rotary kilns, and steady and electric arc furnaces extending from laboratory to demonstration scale. The largest aggregates are a 1 mega volt amp (MVA) electric arc furnace (direct current and alternating current, submerged-arc furnace, and electric arc furnace) with a capacity of 2.5 $m^3$ and a 500 kW TBRC (top blown rotary converter) with a volume of 1 $m^3$. Metallothermic reduction can be performed up to 200 L scale.

***Hydrometallurgy*** is conducted in an aqueous milieu at temperatures up to 250 °C. A leaching and precipitation cascade line (Figure 2) is an example of fill continuous hydrometallurgical processing, enabling recovery of rare earth elements or nickel from >100 kg/d ore. The cascade has a volume of more than 200 L. IME also investigates innovative approaches in hydrometallurgy, using the potential of microwaves, ultrasound, and plasma for intensification of leaching operations. Another major focus is hydrometallurgical recovery of valuable metals from electronic scraps.

***Nanometallurgy*** has been performed for more than 10 years at IME. A liquid precursor is atomized into submicron droplets by using ultrasonic transducers. The droplets then undergo a fast evaporation/drying stage, precipitation, and thermal decomposition/reduction with high surface reaction rates. The desired product of this ultrasonic spray pyrolysis (USP) can be metallic, oxidic or show core-shell structures. Since the decomposition and precipitation occurs in a dispersion phase at the level of several micrometer-sized droplets, USP provides good control of particle size, morphology, and chemical composition as well as phase composition by adjusting solution and process parameters. Figure 3 shows the morphology of a complex nanostructure of silver shell nanoparticles on a zinc oxide core, which have been synthesized for photocatalytic applications by USP. .

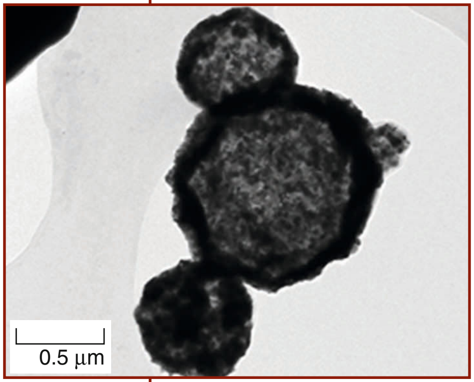


Figure 3. (Top) IME equipment for the production of nano particles. (Bottom) Transmission electron microscopy (TEM) micrograph of complex Ag@ZnO nanostructures synthesized by ultrasonic spray pyrolysis.

***Vacuum metallurgy***, a unique aspect of IME's capabilities, deals with innovative processes for the recycling of used high technology materials, with a current focus on titanium aluminides, rare earth magnets, Al-Li/Al-Sc-alloys, and magnesium. A triple melt route of VIM/electroslag remelting (ESR)/vacuum arc remelting (VAR) allows investigation on improved process routes for superalloys, special steels, and titanium alloys (Figure 4). IME is also using aluminothermic reduction for investigations on tungsten, niobium, and scandium.

The overall focus of IME's pure metal team is new and cost-efficient methods, with a strong emphasis on benchmarking fractional crystallization methods for upgrading electronic metals such as germanium or antimony, as well as aluminum and silver.

***Molten salt electrolysis*** at IME specializes in the synthesis of Ti-composites in chloride-based electrolyte by anodic dissolution of Ti, Al, and V (Figure 5). This route is under research to replace current high-cost methods. Due to the high demand for rare earths, neodymium, and didymium oxide-fluoride electrolysis is conducted with a focus on reduction of harmful perfluorocarbon greenhouse gasses and the automatization of the process. A variety of electrochemical techniques is utilized to determine important process parameters.

Figure 4. IME vacuum metallurgy capabilities encompass: (top) vacuum induction melting, (center) electroslag remelting, and (bottom) zone melting.

## Case Study: New Concepts of WEEE Recycling

Most of IME's studies are not restricted to one of the five research areas. The following case study on recycling waste electric and electronic equipment (WEEE) is an example of IME's deployment of contemporaneous scientific approaches from different angles with the goal of achieving an ideal solution, depending on the composition and morphology of the initial material.

During the last decade, WEEE became a major waste stream in the world, with an annual growth rate of approximately 4%.[1] The metal content of WEEE (and specifically the metal content of waste printed circuit boards) makes this material highly attractive to recyclers for recovery of a broad range of metals. Beside the established base metals like copper and tin, WEEE comprises several precious and critical metals. Apart from these, there is a large share of glass, ceramics, and plastics present.[1,2] As a result, WEEE is a very complex and inhomogeneous waste stream in terms of its chemical composition, as well as particle size and materials structure.

From a metal recycler's point of view, the complexity and inhomogeneity of the input material offer several challenges. The major issue is the high organic content in some WEEE fractions. Less noble trace elements also tend to be lost in the slag and are consequently almost impossible to recover.

To address these issues, IME has launched five research projects in the field of WEEE-recycling. The complete recycling concept works as a modular design principle (Figure 6). Depending on the property of the input material and the desired products, the single modules can be arranged to obtain the most suitable recycling concept. In order to reduce metal losses, the mechanical pretreatment is planned to be minimized, as each comminution and separation step will lead to metal losses and cross contamination.

During the first evaluation, all components within the initial material are regarded as contributing to the process. The energy and reduction potential of the organics, the fluxing potential of mineral phases as well as the volatilization potential of halides, are all considered. Such an autothermal and autogenious process is the desired solution, keeping in mind that a certain degree of pre-conditioning will always be beneficial.

The first module refers to the pre-treatment of the initial material. It can either be compacted or pyrolized. Compaction is applied to fine-grain materials, such as, filter dusts that occur during the shredding and crushing of WEEE. This kind of material contains valuable metals, such as copper and gold. After mixing the fines with reaction agents and fluxes, the mixture is pelletized in order to create an appropriate feed material for a smelting process to recover valuable metals.

Pyrolysis can be deployed for materials which are attached to organic matter. This process step enables an enrichment of the metallic fraction and a separation of halides and hazardous organics without metal losses. Reduced carbon and energy contents also make pyrometallurgical smelting easier to control. Another use for a pyrolysis step prior to the smelting process is the recovery of critical metals, especially indium and gallium via volatilization. A complete understanding of pyrolysis mechanisms helps to develop fully integrated autothermal smelting operations.

The second module refers to the pyrometallurgical treatment. It is subsequent to the first module or defines the starting point of the recycling process. Regarding the recycling of WEEE, the focus at IME lies on autothermal processing of shredded printed circuit boards via direct injection into the liquid slag phase. The preferred reactor type is a TBRC. At this point, contained plastics are used as an energy source to supply the required combustion heat to keep the process autothermal. The final goal is the creation of a liquid copper phase and a foamed slag that quickly captures new feed material and allows immediate full conversion. This process development is assisted by measurements on thermophysical properties of the slag and thermochemical modeling and design of the slag composition.

The third module describes the hydrometallurgical approach. However, this actually serves as the intermediate step between conditioning (first module) and the pyrometallurgical path (second module) and investigates the feasibility of preliminary leaching of gold, which is adherent to the surface of electronic scrap. Due to the high selectivity of this wet chemical process, single metals can be recovered prior to feeding the material into the smelter or a mechanical treatment.

## IME: An Active Core Member of European Raw Materials Networks

The continuously growing public interest in sustainable resource technologies has encouraged the formation of different types of networking structures—local, national,c and Pan-European—to support interdisciplinary problem solving, RWTH has already established a leading role in three competence centers and the high level collaboration in these communities shows the strong international integration of many research institutes in the resource sector. These initiatives include: Aachener Kompetenzzentrum für Ressourcentechnologie e.V. (national amalgamation of more than 20 professors of the RWTH University), German Resource Research Institute GERRI (national association of five leading German research facilities in the raw material sector) and Knowledge & Innovation Community (KIC)-EIT RawMaterials GmbH (120 international partners from the educational sector, research facilities, and industry). These cooperative efforts provide quick dialogue and coordination among industrial companies and compatible research facilities in order to address urgent industrial requests along the entire value chain of raw materials.

Figure 5. Molten salt electrolysis is a major research area at IME.

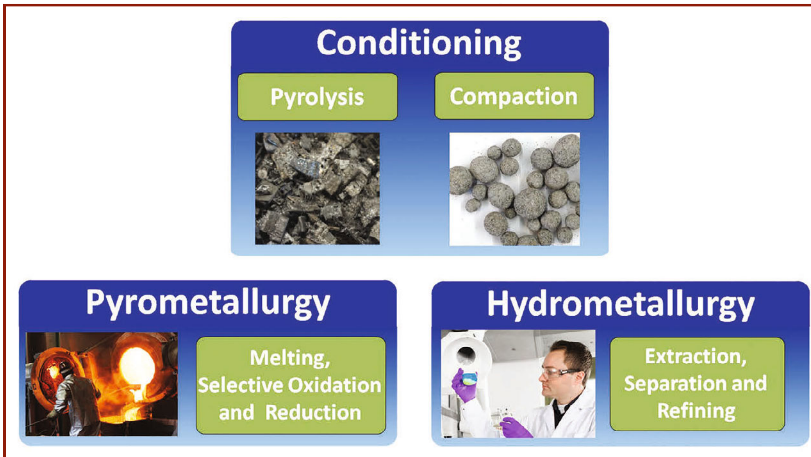


Figure 6. IME's modular design structure for recycling waste electric and electronic equipment.

### Editor's Note:

All photographs presented in this article are credited to Martin Braun.

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