

15 March 2021

Regeneratis D. T1.3.4 Benchmark Report on Metallurgical Processes that are Recommended to be Applied on Past Metallurgical Sites and Deposits

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Version 1.0



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The Materials Processing Institute together with its project partners has the objective of achieving a systematic, long-term beneficial outcome from recovery and regeneration of Past Metallurgical Sites and Deposits (PMSD) in the INTERREG region of Europe under an EU funded REGENERATIS project. Its aims are the innovative circularity to recover raw materials while regenerating the polluted sites.

This report is submitted in fulfilment of the requirements of work package T1.3 and deliverable D. T1.3.4 Benchmark Report on Metallurgical Processes that are Recommended to be Applied on Past Metallurgical Sites and Deposits.

There have been delays to the on-site activities of surveying and sampling due to the Compulsory Purchase Order (CPO) of the land to the South Tees Development Corporation from Sahaviriya Steel Industries PLC (SSI).

Access to the land owned by South Tees Developments Limited (STDL) is managed by the parent company South Tees Development Corporation (STDC) under the newly created organisational structure of Teesworks.

South Tees Development Corporation are an Associated Partner of the NWE-REGENERATIS project and have committed to allow access to the STDL land by the Project Partners subject to the granting of an excavation licence and providing UK health and safety standards and procedures are followed.

The PMSD-1 Teesside site is currently being developed by the STDC – Teesworks commencing with demolition of unused assets on site and the preparation of the land for the establishment of new businesses.

The impact of COVID-19 has limited the accessibility and timing of information.

1 INTRODUCTION

The report provides details of the material processes that are recommended to be applied on PMSDs in order to increase the reuse of resources. It will be used to facilitate the desk data-set for the SMARTIX tool.

The material processes are varied, comprising those of purely physical separation processes and those requiring energy and other materials to effect chemical transformation and for the extraction of valuable resources.

Many of the processes are constrained by rate limitation on thermal, chemical or physical driving forces. Understanding the constraints on the transformational processes is important in the context of commercial viability.

In addition, to the basic requirement of the presence of valuable materials in sufficient quantity, the in-situ form of materials is a key determinant of commercial viability. The in-situ form taken is often varied and complex. Due to the history of the PMSD, the extracted material will comprise a mixture of materials of varying value [1].

The approach to material extraction can be at one extreme a skimming approach in which only high value material is targeted. Other less valuable materials are left in-situ. This may mean that the quantity extracted is small (often of a single product) and that a significant revenue stream from other materials is not taken.

At the other extreme, it may be decided to carry out a complete sweep of an area in which significant material deposits are removed with the intention of maximising re-usable materials both of high value and of a lower value but which still provide an income stream for commercial viability.

If significant land remediation is to take place of the PMSD or the circularity of materials is to be given sufficient importance at the regional or national level, then a new approach is required.

The environmental impact assessment of a site will be a key factor in the remediation strategy and approach taken for material recovery. On polluted sites, particularly those where conventional cost-benefit analysis by operators has historically not provided sufficient justification of site remediation, the new approach is required.

It is recommended that the new approach is based on multi-product, multi-purpose, parallel processing lines. Having multi-product, multi-purpose, parallel processing lines means that those materials of less value can be economically removed.

A strategic asset is required that is of sufficient scale with depth and breadth of technologies deployed to recover materials of value. Due to its processing capabilities commercially viable tolling contracts that simultaneously recover valuable materials and reduce the environmental impact of sites could be undertaken. This could include both legacy PMSDs and current operational sites.

2 THE MATERIAL PROCESSES

The following is a brief summary of the steps required to deliver a viable economic outcome.

Briefly, for each PMSD the steps comprise :

- . Desk top study to recommend areas to survey
- . Surveying including geophysical mapping
- . Excavation using boreholes and test pits
- . Sampling according to standards and procedures
- . Sample preparation
- . Sample testing to standards and procedures
- . Sample reporting
- . Mapping of deposits
- . Estimation of deposit volumes
- . Screening of material processes for materials recovery
- . Screening of viable extraction sites
- . Benchmarking of PMSD for economic feasibility

2.1 THE STAGES OF MATERIAL PROCESSES

The required material processes comprise a hierarchy of stages to deliver the viable economic recovery of materials.

There are several core processes that are common to all material recovery pathways.

The fundamentals of particulate technology underpin nearly all of the innovative material processes. These comprise the following:

- . Material identification
- . Separation
- . Coarse Grading
- . Comminution
- . Fine Grading

Product streams will arise at all stages of materials processing.

For the aggregates market and for other products of relatively low added value, all processing takes place using the core processes.

For higher added value products, the core processing is the starting point to further processing stages.

Further processing steps may include those of pyrometallurgy or hydrometallurgy for the extraction of valuable materials.

2.2 A STRATEGY FOR DEVELOPING INNOVATIVE SOLUTIONS

The traditional products made from iron and steelmaking slags form the benchmarking comparison basis of new proposed solutions for the recovery of materials from PMSDs. These mainly comprise materials for the construction, cement and agricultural industries.

Beyond supplying the traditional products for the construction, cement and agricultural industries there are several factors to consider.

These can be summarised as follows:

- For many production processes, low variability and consistency in feedstock quality is desirable. This is particularly the case for products with tight product quality specifications. The PMSDs materials, however, usually have a large variability in feedstock quality which means that additional processing steps and control solutions are necessary to achieve the same level of product quality. This clearly has implications for both capital and operating costs.
- Most processes for the recovery of valuable resources will not be able to recover all of the feedstock material and additional waste streams are produced. As the objective of the NWE-REGENERATIS project is remediation of the PMSDs in addition to the recovery of materials, those processes that minimise further production of waste or at least produce relatively benign material will be prioritised.
- The rate of remediation of PMSD land area may be in conflict with the rate at which some of the waste material can be extracted. For example, many niche market products may command a high selling price but the market size for the products may be small.
- There may be competition for some of the PMSD waste materials. Some processes may look more commercially attractive in the short term (requiring lower capital outlay) but compromise the potential for a greater revenue stream in the longer term.
- Some processes may require longer to bring to beneficial operation than others. For example, where innovative technologies have been employed. These processes may have the promise of achieving greater benefits, but the timescale may not be compatible with that for remediation or commercial extraction.

- Some processes may benefit from including non-project participating stakeholders who by their involvement can make the projects viable (see 2.3 Industrial Symbiosis).

The likelihood is that several new commercially viable processes will emerge. There then needs to be a process synthesis of the portfolio of projects to optimise the overall outcome.

Factors which can influence this are:

- The use of energy integration across all processes e.g. low grade waste energy from one process used for feed heating for another process.
- The maximisation of any electrical co-generation opportunities where possible.
- The re-use and recycling of waste streams between processes.
- To have a portfolio of products to balance risk and revenue e.g. maintain a sizeable process facility for supplying traditional construction materials while funding the innovative processes for producing higher added value products.
- Flexibility in the planning time horizon for land remediation, particularly in relation to the legacy waste management areas.

2.3 INDUSTRIAL SYMBIOSIS

Many PMSDs are situated in industrial landscapes for common reasons such as location near to naturally occurring resources, a river or estuary, an energy supply network and a well-established transport infrastructure.

For these reasons, other industries external to the steelmaking sector have located to the same areas.

In the case of the Teesside PMSD, the steelmaking sector was followed in the twentieth century by the chemical industry, drawn to naturally occurring salt deposits.

The Teesside PMSD is located close to Wilton International, a large industrial and chemical park. Once owned by Imperial Chemical Industries, the large and diverse operating plants were highly integrated across the site, so that waste by-products from one plant were used by another plant for products, feedstocks or fuels.

The same principle of industrial symbiosis was used at the Teesside PMSD, with steelmaking waste by-products being recycled to the blast furnace, sinter plant or third-party waste recycling companies (e.g., Tarmac, Harsco).

The Cleveland, Redcar and Lackenby iron and steel producing sites operated largely independently from ICI Wilton, as there was no obvious processing inter-dependence between the two sites and they were each largely autonomous. However, independently they both provided the construction industry with waste materials. Fly ash from coal fired plants and granulated blast furnace slag are

both used as clinker reducing additives in the manufacture of cement to improve the quality of the product and offset carbon emissions.

For the Redcar PMSD, there are symbiosis opportunities where this can apply:

- Fly ash and bottom ash.
- Carbon footprint reduction.

2.3.1 Fly and Bottom Ash

Combustion product fly ash finds a limited market outlet in the form of construction materials. The fly ash that does not find a ready market outlet, was in the past stockpiled creating a significant environmental problem.

The composition of fly ash is similar to that of steelmaking slag including the oxides of alkaline metals.

Landfill tax gate fees have increased significantly in recent years which has incentivised operators to look for solutions from the circular economy.

Fly and bottom ash stockpiles reside on PMSDs and neighbouring power and steam raising sites, so there is a common problem to be addressed.

Dry bottom ash can be treated in a similar way to that of blast furnace slag for the marketable product stream generation through comminution and screening. Typically, this involves crushers, magnetic and eddy current separators for ferrous and non-ferrous material respectively. Non-product waste streams comprise an oversize and a fines fraction. The fines fraction usually contains the bulk of the toxic chemicals. This can be vitrified and made into a reusable product using an arc furnace [2].

The arc furnace can be used for fly ash, for separated fines from bottom ash and for steelmaking dusts and sludges. The furnace uses a carbon electrode in a reducing atmosphere and allows extraction of the metal content from a vitrified slag. Low melting point metals such as zinc and lead are collected as a re-sublimated marketable product.

Other technologies such as rotary hearth reduction offer alternatives for the reduction and extraction of metals from process dusts (considered in Section 3.1).

2.3.2 Carbon Footprint Reduction

All industries are looking to reduce their carbon emissions and particularly those in the energy intensive industries.

Unfortunately, the failure to reduce the impact of the cost of carbon has contributed to the demise of some industries. As the free allocation of carbon allowances was reduced under the European

Union Emission Trading System (EU-ETS) and the market price of carbon increased, the cost of carbon emissions resulted in a significant burden on operating companies.

Carbon capture, usage and storage (CCUS) is still not an economic alternative for industry without significant government support.

One possibility to making CCUS work for operators is carbon sequestration.

Cement manufacturers are one of the largest producers of carbon dioxide using approximately 0.87 kg CO₂/kg cement. Approximately 50% of the carbon is generated from the calcination process with 40% from fossil fuel used in the calciner furnace and 10% from quarrying, transport and material pre-processing.

Calcium carbonate is the main process feedstock requiring 0.53 kg/kg cement.

The basic process of cement production is the calcination reaction of heating calcium carbonate to approximately 1450 °C. Calcium oxide is produced with the evolution of carbon dioxide.

Cement manufacturers have concentrated on reducing the contribution of carbon in the fuel but have yet to make significant progress on the contribution of the calcination reaction.

One process for locking up the CO₂ in the form of a stable material is the accelerated carbonation of steelmaking slag [3]. This can be undertaken in a reaction in an aqueous solution of the slag in powder form under pressure and at an elevated temperature.

The minerals in the slag such as calcium and magnesium oxides, silicates and hydroxides are reactive with carbon dioxide. Other features of accelerated carbon technology are:

- Amorphous or crystalline carbonate formed.
- Steel slags can capture CO₂ directly from flue gas.
- Carbonate reduces the pH.
- Stabilises metals such as lead, zinc and copper.
- The carbonate product locks in possible leachates in addition to the carbon dioxide.
- High value products can be engineered.

However, on an industrial scale the processing of the liquid waste requires a technical solution.

Another sequestration process is that of producing precipitated calcium carbonate (PCC) [4]. PCC finds use as a filler material in the surface coating of paper and in paints and plastics.

The estimated power requirements of accelerated carbonation are 1300 – 2750 MJ/tCO₂ [2].

Wholesale electricity prices are published in several sources.
<https://www.elxon.co.uk/knowledgebase/where-can-i-find-details-of-wholesale-prices-of->

electricity-in-great-britain/. Baseload power prices in the UK are 43.39 euro/MWh <http://www.apxgroup.com/>. Based on 0.92 £/euro, the range of energy cost is £14.41 - £30.49. Data is taken on 20 September 2020. The daily market price of CO₂ EU-ETS is 26.38 euro/tCO₂ (21 September 2020) <https://ember-climate.org/data/carbon-price-viewer/>. This equates to £24.27/tCO₂.

2.4 METALS RECOVERY FROM SLAG

Prior to SSI Teesside entering administration and ceasing production, the recovery of metals from slag was an established commercial operation undertaken by Harsco located on the Teesside PMSD. The principal products comprised iron units taken from steelmaking slag.

Metals arise in slag from two sources:

- Metal alloy droplets which are mechanically trapped in the slag phase.
- Metal oxides or sulphides chemically dissolved in the slag.

Due to the low iron content in blast furnace slag, it is only commercially viable to recover iron from steel slag.

Iron is usually found in steel slag in the form of magnetite (Fe₃O₄).

The mineralogy of steel slag [5] comprises silicates, aluminosilicates and calcium-alumina-silicates. The varying compositional fractions include merwinite (3CaO.MgO.2SiO₂), olivine (2MgO.2FeO.SiO₂), dicalcium silicate (2CaO.SiO₂), tricalcium silicate (3CaO.SiO₂), dicalcium ferrite (2CaO.Fe₂O₃), tetra calcium alumino-ferrite (4CaO.Al₂O₃.Fe₂O₃), the Reduced Oxide phase (CaO-FeO-MnO-MgO solid solution) and free lime (CaO).

The recovery of metals can be undertaken by:

- Physical recovery.
- Chemical recovery.

The commercial viability of physical metals recovery is particularly dependant on the asset sunk costs and the economies of scale. For any single UK Iron and Steelmaking PMSD the recovery of metals from waste stockpiles is broadly cost neutral [6], i.e. the cost of recovery is comparable to the return from the sale of the metal products. This is due to the additional costs of removal and processing of the waste materials in comparison to waste being supplied from an operational steelworks where waste control standards are in place.

2.4.1 Physical Recovery

Sorting by comminution and sizing is an effective concentration method for the recovery of metals.

Due to differences in brittleness and/or crystallite/grain size in the phases, the fracture of particles often occurs at the interface between the phases. Sizing, therefore, is a way of splitting materials into lean and rich streams.

Physical recovery relies on differences in density (gravity separation), magnetic susceptibility and wettability.

The application of comminution, sizing and separation can be undertaken in a myriad of different ways. To optimise the process for excavated material of unknown origin is a non-trivial problem.

Clearly, the efficiency of metal recovery is dependent on the in-situ distribution of metal within the excavated material. Some of the metal will be both mechanically and chemically bound. The distribution of chemically bound metal will be dependent on the process chemistry as well as the process conditions of the slag post-treatment, e.g. cooling regime.

Blast furnace slags are often cooled quickly and produce an amorphous slag with the metals remaining dissolved in a glass matrix structure. This makes the recovery of the metals difficult. When a metals recovery plant is operated alongside an operational steel works, material of a known origin is processed. The metals recovery plant may also directly control the rate of cooling of the slag to ensure a desirable phase structure is produced to maximise metal recovery.

In the context of a PMSD, there may be no prior knowledge of the material, so that there is an additional problem of identification to be addressed in order to determine the optimum way of recovering the metal content.

2.4.2 Chemical Recovery

There are added benefits from undertaking the chemical recovery of metals. This can either be undertaken using pyrometallurgy or hydrometallurgy.

Some of the benefits are :

- Improved slag volume stability, e.g. by the removal of CaO.
- Reduction in the leachability of heavy metals, e.g. Cr, Ni, Cd, V.
- Feasible for fine-grained waste, e.g. BOS sludge, oily millscale.
- Reduction in phosphorus from the metal product.
- Improvements to the phase properties by the addition of SiO₂ (sand) and Al₂O₃ (bauxite).
Fly ash can also be used (see 2.3 Industrial Symbiosis).

However, many of these benefits only arise for finely ground feedstock which invariably requires additional comminution costs over those employed for the aggregates and cement markets.

There are two areas of pyrometallurgy technology which are of interest for the recycling of materials from steelmaking slag and which are considered in this report. These are:

- Rotary Hearth Furnace.
- Arc Furnace.

Rotary hearth furnace (RHF) technology has been developed commercially to produce a direct reduced iron (DRI) or hot briquetted iron (HBI) product that has a worldwide commercial market. In addition, it is also used to recover the volatile metals of zinc and lead in the steel slag.

Rotary Heath furnace technology is discussed in more details in Section 3.1.

Arc technology has been developed at the commercial scale for processing a broad range of industrial furnace wastes including steelmaking slag. This is discussed in Section 3.2.

2.5 RARE EARTH ELEMENTS RECOVERY FROM SLAG

Rare earth elements (REE) such as neodymium (Nd), praseodymium (Pr) are found in blast furnace slags at the parts per million scale. Typically, Nd (31 ppm) and Pr (8.6 ppm). This is approximately 1/70th of the concentration found in the natural ore.

The challenge is to find ways to make extraction commercially viable while not resulting in the generation of new waste streams.

There are several possible ways to make this happen:

- Recovery in conjunction with other raw materials.
- Through a minor modification of an existing process.
- Through lower cost separation technologies.

For example, REE can be concentrated using the same physical separation processes employed for comminution, screening and the magnetic separation of metals for the aggregates, fertiliser and the cement industries.

If a way can be found to concentrate the REE, achieving a composition comparable to that of the ore concentrate, the product will have a ready market for existing REE refiners.

This would potentially be a win-win for the slag processing operators, providing that the new product is complementary to its existing business and does not adversely impact the existing revenue streams.

The ideal situation would be if the REE could be extracted from the tailings of the existing process. Alternatively, a small purge stream could be taken from the existing process taking up available surplus machine capacity to undertake pre-processing comminution and screening prior to feeding the REE extraction process.

3 LONGER TERM STRATEGIC SOLUTIONS

The STDC recognises in their strategic plan [7] that parts of the PMSD Teesside site will require longer term solutions due to the challenges they pose for economic development. This is particularly true for the Waste Management area comprising the SLEMS and Hi Tip areas which have an opportunity and a cost to their re-development. The opportunity is in the form of considerable metal resources and the cost is of treatment of those resources and site remediation.

Currently, no existing UK operational iron and steelmaking site has a long-term solution to many of its difficult waste streams, including dusts, sludges and oily mill-scale. These are sent to landfill usually on site in slag heaps or lagoons. Derogation of Health and Safety Executive/Environment Agency mandated improvement notices based on enacted European Union (EU) law has frequently been sought by the operating companies. Specifically, the implementation of EU published Best Available Technology (BAT) cannot be justified for a single site such as those at Scunthorpe or Port Talbot due to the considerable cost for a single operator to bear. Currently there is no obvious solution to this problem.

One of the objectives of the NWE-REGENERATIS project is to formulate a benchmark model for PMSDs but in many respects the issues are also highly relevant to operational steelwork sites.

Furthermore, there is a possible synergy by addressing both sets of problems for current operators and owners of PMSDs in the form of a nationally operated reprocessing asset that in addition to reprocessing the legacy wastes held in stockpiles around the country would take the daily arisings of waste streams from the operational steelworks.

Controlled waste taken from operational steelworks would help to offset the additional costs of legacy wastes.

As a result, the implementation of BAT could be employed. In the following section this is explored in more detail based on work undertaken at the Materials Processing Institute.

3.1 DESKTOP INVESTIGATION – ROTARY HEARTH FURNACE

The treatment of steelmaking dusts and sludges containing significant iron units and relatively volatile metals such as zinc and lead under furnace conditions has been addressed by a study [8] examining the technical and economic feasibility of recycling the materials to UK and European based metal refining and production facilities.

The established manufacturing route for recycling iron units from steelmaking dusts to iron and steelmaking plants is via a rotary hearth furnace (RHF). This is used to produce a pseudo form of Direct Reduced Iron (DRI) which can be recycled in a blast furnace. The current global market for DRI is dominated by gas-based shaft processes which produce a high-quality iron product for use in steelmaking. The total expected metallic iron content is 83-90% and a carbon content of 1-4%.

There are two competing technologies for DRI production - Midrex, which is the type operated by ArcelorMittal's Hamburg plant, and HYL/Energiron.

There are relatively few RHF plants in the world, with the main ones in the US and Asia with the exception of JSW's site in Piombino, Italy.

Zinc and lead can be recovered from a RHF as a by-product; however, the main revenue stream would be derived from the pseudo DRI product due to the relatively low zinc and lead content of BOS steelmaking dusts and sludges. The revenue parity between iron and zinc occurs at approximately 10% zinc.

Steelmaking wastes typically contain 1-1.5% zinc from a blast furnace (BF), 1-4% from a Basic Oxygen Steelmaking (BOS) and 10-25% zinc from an Electric Arc Furnace (EAF). The variation in BOS and EAF material is due to the amount and quality of scrap used. Where galvanised scrap is used, the zinc content tends to be at the upper end.

Partial recycling of BF and BOS dust is currently undertaken via sinter used in a BF but subject to sinter plant quality constraints on the metallic constituents, including zinc, which limits the amount of material that can be recycled.

The material that cannot be technically or economically recycled has historically gone to stockpiles, landfill or lagoons at the site of the steel plants. This includes PMSD-1 Teesside's SLEMS area.

Due to the lower quality DRI derived from BOS steelmaking dusts, the economic viability of RHF technology requires relatively large-scale throughput of waste material.

Corus reported [9] the following legacy stock holdings of steelmaking waste:

- 0.5 Mt BF/BOS slurry in the SLEMS, Teesside
- 1.0 Mt BF/BOS mix at Crosby Landfill, Scunthorpe
- 2.0 Mt BF/BOS mix at Llanwern Lagoons
- 1.8 Mt BF/BOS mix at Port Talbot

In addition, there are high zinc containing wastes at Liberty Speciality Steel plants and at Port Talbot and Llanwern which have used high galvanised (zinc coated) scrap steel.

The current annual dust and sludge (filter cake) arisings from steelmaking at British Steel Scunthorpe and Tata Steel Port Talbot are approximately 40 kt and 50 kt respectively.

The large capex required for a rotary hearth installation is currently a disincentive to UK operators. The decision process is complex but has to include the requirement for state funding in addition to the expected volume and value of recovered materials.

3.1.1 DRI/HBI as an Alternative Raw Material In Steelmaking

DRI is produced from lumps or pellets of iron ore by removing the oxygen in a reduction process. A reducing gas derived from either coal or natural gas is used as the reductant. The process takes place at high temperature, below the melting point of the ore which means the ore retains its solid form, but due to the loss of oxygen becomes lighter and highly porous.

DRI is highly reactive due to its porous structure giving it a large surface area. This means DRI will readily oxidise if it becomes wet and in doing so give off heat and hydrogen. This makes storing large quantities in a ship's hold for transport dangerous. To combat this DRI is modified into a form known as Hot Briquetted Iron (HBI) for transportation. This process simply compacts the porous DRI lumps or pellets and reforms them into a uniform shape and size that has a significantly smaller surface area and hence reactivity.

HBI is used in both BOS and EAF steelmaking and brings several productivity and quality improvements. The benefits of HBI come from three important attributes:-

- Consistent known chemistry.
- Low levels of unwanted residual elements.
- High bulk density of iron units.

Steel scrap is supplied to steelmakers in a range of grades with each grade consisting of scrap from a variety of sources. Steelmakers also reduce the risk in their supply by using several suppliers. This means that consistent usage of the same amount of the same grade of scrap can have differing properties once they become liquid steel. Variation in the primary steelmaking process increases the difficulty of meeting the chemical specification for the grade of steel being produced. This leads to an increase in the time required for composition adjustments in secondary steelmaking. HBI can achieve a much tighter chemical specification than that of scrap and hence can increase steelmaking consistency and productivity.

As well as having a more consistent specification, HBI can offer much lower levels of unwanted residual elements than scrap. The substitution of scrap for HBI in an EAF can be used to increase the quality and grade of steel that would otherwise have been created. In the BOS plant the use of HBI can aid the control of sulphur through the process which increases the quality of the steel. HBI can also be used as a coolant in the BOS plant when overheating towards the end of a blowing cycle.

HBI is a very compact form of iron units compared to scrap steel. This higher density eases material handling and reduces charging time which further increases productivity.

Where plants are co-located, DRI can also be used in EAF steelmaking without allowing it to cool. This is known as hot-charging and brings additional benefits over the use of HBI. As the DRI is not cooled it is charged to the furnace at a higher temperature, typically around 600 °C. This significantly reduces the heating and energy consumption required, to raise the DRI up to the melting point. The reduced time spent heating the DRI has two additional benefits. It reduces the electrode consumption, a key consumable expense in EAF operation, and it reduces the overall time taken for each melt and hence increases the productivity of the steelmaking plant.

At present, there is no active market for DRI/HBI in the UK.

3.1.2 Commercial DRI/HBI Production Processes

There are two main types of DRI production process; gas shaft furnace and coal based rotary furnace. A high-level process flow diagram for these two processes is shown in Figure 1 [10].

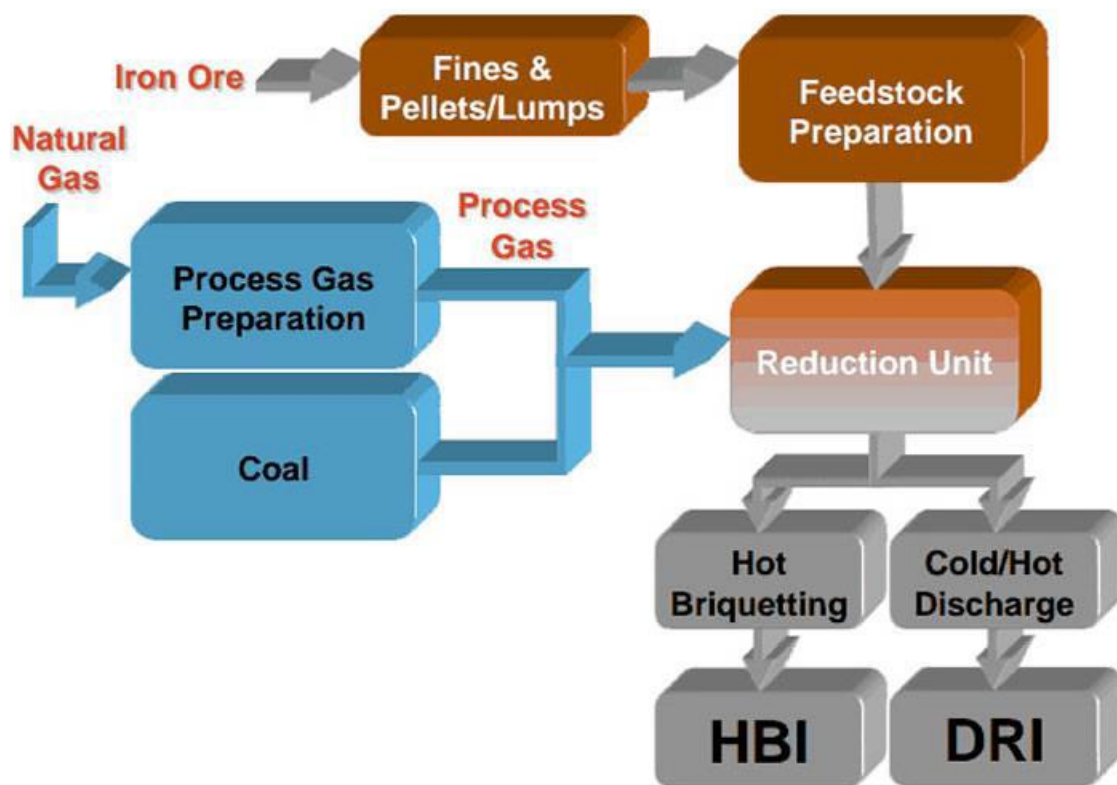


FIG. 1 Overview of DRI/HBI Process

Nearly all of the coal based rotary hearth furnaces used for DRI production from iron ore, are based in India and are largely for domestic steelmaking operations with none being exported to the European market. Gas based shaft furnaces account for over 80% of the world's production [11] and all of the DRI traded in Europe.

3.1.2.1 Gas Shaft Furnace Process

There are two gas-based shaft furnace technologies in use. The Midrex process accounts for approximately 80% of DRI produced by this process [12] with the HYL/Energiron process accounting for the remainder.

Both these technologies utilise a shaft furnace in which iron ore in the form of 10-30 mm sized lumps or pellets are top fed whilst the process gas (the reductant) is feed from the bottom. The iron ore flows downwards due to gravity and gets reduced by the up-flowing process gas. The temperature

of the furnace in the two processes are similar at around 800-850 °C. The reducing gas is commonly generated from a high methane containing natural gas.

The only European based DRI production facility is ArcelorMittal's Midrex plant in Hamburg, Germany. Future zero carbon aspirations are also leading to work assessing the longer term feasibility of green hydrogen as the process gas.

3.1.2.2 Rotary Hearth Furnace

Coal based DRI production utilises either a rotary kiln type furnace such as the Stelco-Lurgi/Republic-National (SL/RN) process or a rotary hearth furnace (RHF) such as the Rediron process (Paul Wurth). The principle behind these processes is that the coal is used as a heat source as well as providing the reducing gas. The coal and the iron ore are in direct contact with each other and controlled combustion of the coal produces carbon monoxide which reduces the iron ore as they travel through the furnace. A rotary kiln furnace comprises an inclined cylindrical shell with coal and iron ore added at the higher end and DRI extracted at the lower end. It is the technology used for nearly all the coal-based production of DRI from iron ore.

RHFs are not in widespread use for large scale DRI production from lumps or pellets of iron ore but are a proven technology for recycling of steelmaking wastes into pseudo DRI [13]. A RHF consists of a flat circular hearth rotating inside a larger diameter stationary furnace. This process has the ability to handle sludges and slurry arising from the BF and BOS route as well as dusts from the EAF route. There are seventeen plants, either operational or planned, located worldwide mostly in the USA and Asia with the one European based plant in Italy operated by JSW Steel.

3.1.2.3 Technical Requirements

The globally traded DRI is produced by two technologies that both utilise a gas shaft furnace process. This means there is a reasonable standardised set of market specifications encompassing the chemical composition and the physical properties as shown in Table 1.

TABLE 1
REQUIRED MARKET SPECIFICATIONS [14]

Property	DRI	HBI
CHEMICAL COMPOSITION		
Total Iron (FeT)	89 – 94	89 – 94
Metallic Iron (FeMet)	83 – 90	83 – 90
Metallization	92 – 96	92 – 96
Carbon (C)	1% – 4%	1% – 4%
Phosphorous (P)	0.005 – 0.09	0.005 – 0.09
Sulphur (S)	0.001 – 0.03	0.001 – 0.03
Gangue*	3% – 8%	3% – 8%
PHYSICAL ANALYSIS		
Bulk Density (tonnes/m ³):	1.6 – 1.9	2.4 – 2.8
Apparent Density (tonnes/m ³):	3.4 – 3.6	5.0 – 5.5
Typical size (mm)	4.0 – 20.0	30 x 50 x 110
Proportion >5mm Fines/Chips	5% max	5% max

*residual unreduced oxides, mainly SiO₂ and Al₂O₃, (also includes CaO, MgO, MnO)

The pseudo DRI produced using a RHF and steelmaking wastes, particularly those from the BF process, is unlikely to have as high an iron content as the specifications in Table 1. This makes it unattractive to the part of the DRI market that utilises it as a scrap replacement in EAF steelmaking, but it would still have value as a BF feedstock. An in-depth sampling of the steelmaking wastes combined with predicted analysis of the pseudo DRI created, would allow the value in use for a BF to be calculated. BOS dust is typically much higher in iron than BF dust so may be suitable for EAF use.

3.1.2.4 Zinc By-Product

Zinc is a commercially valuable by-product of the RHF that arises as off-gas dust/powder rich in zinc and lead in the form of crude zinc oxide (CZO).

About 90% of the zinc and lead in the waste feed to the RHF is volatilised and captured as CZO [9].

In Germany, DK Recycling operate a dedicated sinter plant and blast furnace to process steelmaking dusts and sludges arising from blast furnace and basic oxygen furnaces [15], with the blast furnace being fed by 100% sinter. Both plants have been optimised to handle the high concentrations of zinc, lead and alkalis which in a conventional blast furnace would result in refractory degradation and operational problems.

DK Recycling operates a strategic partnership with nine different steelworks from six European countries. In 2017 419 kt/yr of ferrous waste was recycled to produce 259 kt/yr hematite pig iron (92% Fe) for the European foundry industry and 17 kt/yr zinc concentrate (65% Zn) for the zinc smelting industry. The recycling rate achieved is 98% of the steelmaking dusts.

3.1.2.5 Value in Use

The value-in-use is a function of the iron and zinc content of the BF, BOS and EAF waste feedstock. Blending with virgin material is necessary to achieve both compositional and structural requirements.

The current barriers to recycling BF, BOS, EAF dusts back to the steelmaking process are zinc (above a threshold maximum), moisture and fine particulates.

New build commercial plants for the recovery of iron and zinc can achieve a utilisation of solid waste (dust and sludge) of over 97% at rates of 600 te /day processed solid waste [9].

From a 200 kt/yr dust recycling plant, based on an average of 2% zinc content, the production of CZO would be approximately 4.2 kt/yr based on a conversion rate of 67.7% (dust to CZO) and an 80% ZnO purity. At a CZO market price of US\$777 /t, this equates to an annual revenue stream of £2.6M [9].

3.1.2.6 Process

Currently, only pyrometallurgical processes can achieve an adequate separation efficiency of zinc from iron. Hydrometallurgical processes have a lower recovery rate of zinc due the presence of zinc ferrites in the dust. Zinc ferrite is very stable and difficult to decompose with hydrometallurgical processes. However, the pyrometallurgical process can break down the ferrite into zinc oxide.

A large amount of dust and sludge wastes can be recycled to the blast furnace (BF) but due to the accumulation of zinc (which condenses out of the waste gases and adheres to the BF walls) another method of recycling is required.

One proven recycling process is the metallised pellet producing process. Sludge is de-watered (via a filter press) and pre-heated (900-1100 °C) on a travelling grate and then heated at high temperature (1200-1400 °C) in a RHF to produce DRI quality iron for a BF or EAF. The zinc is removed from the agglomerated raw materials through reduction and gasification and is collected as a secondary dust. The typical recovery rate of the zinc contained in the BF/BOS is greater than 85%. The remaining iron (with low zinc content) can be recycled as a high metallised DRI in a BF or EAF.

Quality factors in the RHF production of metallised pellets are the metallisation rate, compressive strength and dezincification rate. Metallisation and dezincification rates increase with temperature and time. The compressive strength is a function of the sintering time, additive (flux) quality/quantity and the method of reduction.

In order to optimise the quality factors of the BF/BOS sludge pellets, experimental data is required to understand the role of the drying, pre-heating and the direct reduction stages.

The process for producing pellets, briquettes or extrusions depends on the amount of blended raw materials. Where the total elemental iron content in the BF/BOS is high, the cost of the blended raw materials is lower, favouring the production economics.

Dezincification rate is optimised by the cooling and capture of the zinc particulates in the form of zinc oxide.

Pyrometallurgical processes do face significant challenges. The process economics are driven by the feed zinc and iron content. The energy consumption is high. There is a requirement for gas cleaning. The presence of chloride and fluoride salts cause corrosion problems necessitating the use of expensive alloys as construction materials.

Also, the ability to produce zinc oxide of marketable quality is dependent on further post-treatment stages after zinc oxide dust collection from a bag filter. In addition, the separation quality is not always good, with other volatile species present depressing the zinc recovery rate.

In some processes the crude zinc oxide is further processed in a calcining kiln to produce metallic zinc. The lead and other metals are separated at this point in the process and the zinc feedstock is sent for further processing into refined zinc. The lead is separated so it doesn't go into the zinc recovery operation and contaminate the equipment. The lead fraction in the form of lead carbonate is sent to a primary lead smelter. The separation of lead from the zinc is not 100% with the zinc product containing up to 1.5% lead.

3.1.3 Product Technical Specification

The technical requirements of DRI and zinc are defined by physical, structural and chemical factors.

3.1.3.1 Physical Specification

The DRI bulk and apparent densities should be in the range 1.6-1.9 g/cm³ and 3.4-3.6 g/cm³ respectively.

3.1.3.2 Structural Specification

Flue dusts frequently comprise the agglomeration and inclusion of small particles inside large matrix phases making the separation of zinc poor and with the attendance of other undesirable constituents, e.g. heavy metals. This is a generic problem that is not specific to one class of dust source.

The particle size distribution of the zinc oxide must be controlled.

The particle shape will tend to be spherical because the solid zinc oxide arises from a vapourisation and condensation process.

The relative ease in which zinc vapourises and enters the off-gas stream in a rotary kiln or rotary hearth furnace depends on the morphology of the BF, BOS and EAF particles. In some of the particles, the zinc is agglomerated at the surface, so would naturally enter the gas stream first during heating

of the particle. This is also the case for other species with relatively low vapour pressure such as lead which naturally follows zinc in the processing path.

3.1.3.3 Chemical Specification

The metallic chemical balance of DRI should ensure that gangue material is minimised.

Typically, the composition will be:

C 2.5-4.3% Si 0.2% Mn 0.1% P 0.06% S 0.015-0.05%

Silicon will normally be low because the RHF is operated at a lower temperature than other hot metal production processes.

Phosphorous content depends on the chemical composition of the iron ore. All the phosphorus is reduced and retained in the pellets.

Sulphur content is a function of the sulphur content in the reductant coal. Typically, 60% sulphur will be retained in the DRI.

In order to prevent accumulation of zinc and damage to the BF or BOS plant, the zinc content of the BOS dust should be reduced to below 0.4 wt% to ensure that it can be safely recycled in the iron or steelmaking process. This will not normally be a problem using the RHF technology.

The performance of a blast furnace is strongly affected by the presence of alkalis due to the lowering of the melting point temperature of iron ore and sinter. Alkaline elements accumulate in the blast furnace due to cyclic reactions and result in a loss of production, e.g. loss of burden permeability, refractory damage. Thus, removal of alkalis is important before recycling dust or sludge back to the BF. The RHF process assists in the removal of alkalis with low melting alkali compounds vapourising along with zinc.

Lead and cadmium with traces of chromium and arsenic are found in EAF dust, so care is required to ensure that EAF dust as a source of zinc does not fail toxicity tests.

3.2 DESKTOP INVESTIGATION – ARC TECHNOLOGY

Arc technology is the conversion of electrical energy to heat energy allowing the melting and gasification of waste materials and in the process, due to the high temperatures produced, can breakdown organic pollutants to simpler molecules such as carbon monoxide and hydrogen.

It can be used in furnaces to convert a broad range of industrial and domestic wastes. These can vary from metallurgical processing wastes to municipal wastes.

In the context of PMSD – Teesside, it could be used to recover the valuable metal content from steelmaking slag such as iron, and zinc under reducing furnace conditions.

At the same time, it can be used to produce beneficial construction grade materials such as hydraulic powder, metallurgical powder and cement clinker.

The volatile materials such as alkalis, halides and low melting point metallic species such as zinc and lead are processed via a gas processing plant with zinc oxide sold as commercial grade product.

However, while the technology exists to process steelmaking wastes, it has some significant production costs, most notably from electrical energy. The commercial viability of the process hinges crucially on the composition of the waste material. For example, waste having a high valuable metallic content or waste that due to its pollutants has a high gate-fee for waste disposal. Historically, landfill costs have been relatively low in comparison to the recycling costs, so there has been no commercial incentive to recover the materials.

3.2.1 Furnace Design Based on Arc Technology

There are several furnace designs available that have been developed from pilot plants to commercial production facilities. However, the throughput quantities are typically an order of magnitude lower than those for RHF production facilities. Their advantage is that they are very flexible on feedstock composition and can be used to process hazardous material to create relatively inert products.

3.2.1.1 In Plant By-Product Melting

The In Plant By-Product Melting (IPBM) process was developed jointly by a number of European collaborators [16].

Pilot plant trials were undertaken at Swerea MEFOS and full-scale plant trials at SSAB EMEA Works Lulea [17].

The furnace is configured with a DC electrical supply with a hollow cathode and an anode built into the base of the furnace covered with refractory. The charge material, reductant and slag modifiers are introduced via the cathode tube. The furnace has tapping points for the metal alloy and the slag phases. The volatile components and off-gas are taken to a treatment plant where the by-products are separated from the secondary waste stream.

A diagram of the furnace configuration is shown in Figure 2.

The reduction degree and slag composition are controlled by the reductant/slag ratio and the addition of slag formers such as silica sand or bauxite.

An anthracite/slag rate of 130 kg/tonne slag is required. The reported energy consumption at a feeding rate of 1 tonne cold BOS slag per hour is 1.6 MWh/tonne.

In general, the slag/metal weight ratio is about 4 to 1, which corresponds to a slag/metal volume ratio of about 12 to 1.

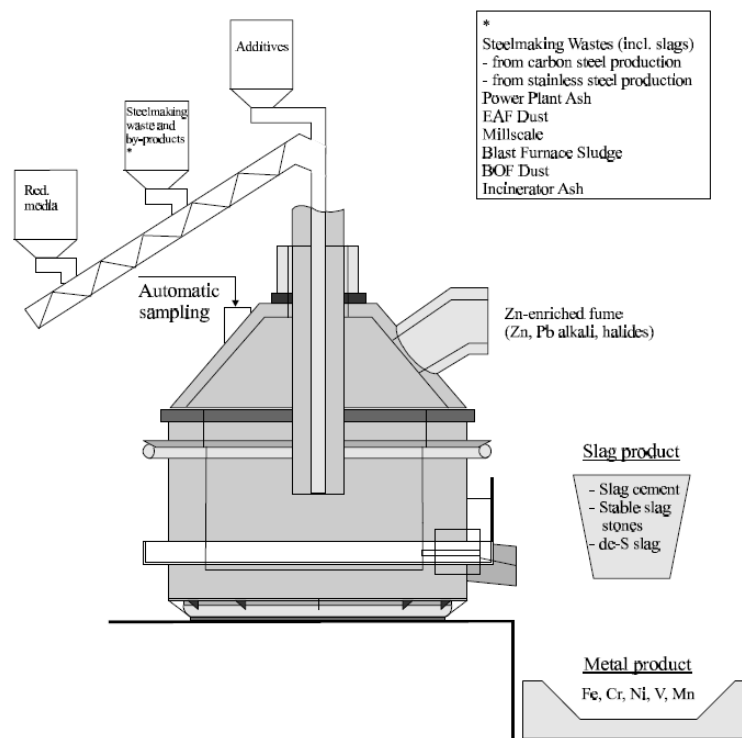


FIG. 2 IPBM Plant Configuration

The metallurgical waste from steelmaking sites typically comprises the four major fractions provided in Table 2.

TABLE 2
TYPICAL FRACTIONS OF METALLURGICAL WASTE

	Main components
Fraction A: stable oxides	CaO, Al ₂ O ₃ , MgO and SiO ₂
Fraction B: reducible oxides	FeO, Fe ₂ O ₃ , Cr ₂ O ₃ , NiO, MoO ₃ , MnO
Fraction C: easy to evaporate	ZnO, PbO, CdO, alkalis and halogens
Fraction D: organic waste	C-H compounds such as plastics or paints

The waste charge material requires reducing in size to a maximum of a few millimetres, so is ideal for processing dusts and sludges that arise from off-gas treatment by wet or dry scrubbing. Approximately, 20-25% of all steelmaking slag production is in the form of fine grade material.

A broad range of materials have been successfully treated including blast furnace slag, basic oxygen steelmaking slag, dusts and sludges, electric arc furnace dusts and oily millscale residues.

The core objective of the IPBM furnace is the ability to handle all the recycling issues of waste materials from an integrated steelworks in a dedicated facility and free-up the blast furnace and BOS furnace to concentrate on production and the optimisation of the product ranges.

The reduction of FeO and P₂O₅ is relatively easy compared to MnO. The recovery reported [16] of Fe was over 95% and zinc over 99%.

The environmental compatibility and mechanical properties of the slags are improved after slag reduction.

The leaching of heavy metals from the reduced slag by-products is 10-100 times smaller than that of the slag feedstock. The volume stability of the reduced slag is also much improved over the slag feedstock and of a commercial grade quality.

The three slag by-products all perform well against their comparable commercial counterparts. Cement clinker meal (70.6% limestone, 19.4% clay rock and 10% IPBM slag) has been successfully tested to EN 196 and compared with Portland cement.

A suitable hydraulic binder is produced for the cement industry by granulation in a water tank or by water jet-spraying following tapping of the slag.

A commercial grade metallurgical powder is produced on cooling which is close (and acceptable in quality) to synthetic calcium aluminate.

Pilot plant trials have also been undertaken at Swerea MEFOS on the reduction of BOS slag using a 5 MVA AC electric arc furnace [17]. This is shown in Figure 3.

The BOS slag, reductant and slag additives were fed via a chute into the EAF. Slag additives were added to control the slag temperature at 1650 °C. A final reduction stage was done by injection of ferrosilicon (FeSi) and/or aluminium powder into the molten slag.

The metal recovery rates were 92-99% Fe, 96-99% P, 70-92% Cr, 50-96% Mn and up to 99% V.

The reduced slag compositions are shown in Table 3.

The water granulated reduced slag was shown to have equivalent properties to those of granulated blast furnace slag for cement production.

For recovery of metals on an operational site, there are benefits from hot charging the EAF to reduce the electrical energy consumption. Again, a two-stage reduction process would be employed with a carbon reductant followed by slag additives.

A two-stage enrichment blowing process has been developed by SSAB EMEA works using peroxidation of the slag [19] based on work undertaken at Japanese steel plants for the removal of phosphorus [20]. In this manner, the composition of the vanadium was approximately doubled.

Even more significant is the potential for larger recovery of vanadium from the two-stage product alloy which has been shown to concentrate in the spinel phase with negligible phosphorus content as shown in Table 4.

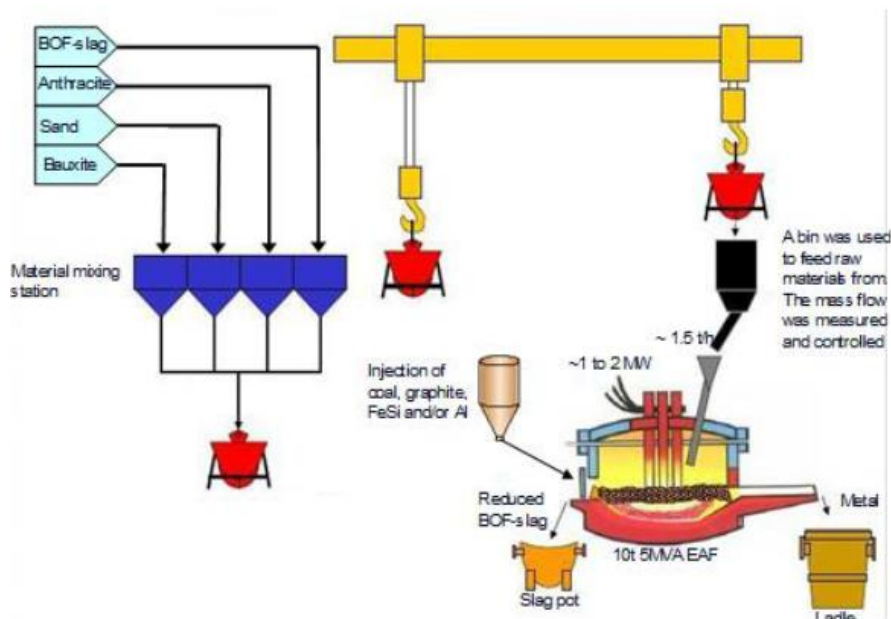


FIG. 3 Pilot Plant AC EAF Setup

TABLE 3

REDUCED SLAG COMPOSITION FROM EAF TRIALS

	%Fe	%V	%CaO	%SiO ₂	%MnO	%P ₂ O ₅	%Al ₂ O ₃	%MgO
Slag 1	0.08	0.03	41.6	37.4	0.32	0.01	2.9	17.2
Slag 2	0.07	0.03	37.6	14.2	0.21	0.01	37.9	11.2
Slag 3	0.64	0.04	37.2	23.5	0.34	0.01	27.9	11.9

TABLE 4

PHASE ANALYSIS OF A TWO-STAGE OXIDATION SLAG

	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	CaO	TiO ₂	V ₂ O ₅	Cr ₂ O ₃	MnO	FeO	Total
spinel	0.7	0.6	0.2	0.0	0.5	4.5	34.9	15.3	10.9	38.0	105.6
kirschsteinite	1.3	0.1	33.8	0.4	34.2	0.6	0.5	0.2	11.6	18.4	101.1
"glass"	0.3	0.1	31.2	5.4	52.1	0.2	1.3	0.3	4.2	5.8	100.8
wüstite	0.8	0.1	0.3	0.0	0.5	0.3	1.6	0.3	15.6	80.5	100.1

Conventional BOS slag with low vanadium content has also been processed in the IPBM process where iron, phosphorus and manganese are recovered in the metal phase and three slag products are produced, as discussed previously.

The IPBM process can also be used for recovery of nickel and chromium from fine grained wastes (EAF dust, mill scale) from stainless steel production. In the context of industrial symbiosis, any future EAF investment on the Teesside site could beneficially use the IPBM process to recovery the valuable metals from the waste streams, in addition to the recovery of valuable materials from the legacy steelmaking wastes.

The IPBM process can also be used to recover zinc and lead from carbon steel dusts and sludges such as occurs in BOS oxide residues at the SLEMS of PMSD – Teesside.

Again, in the area of industrial symbiosis, the IPBM process can also be used for the AshArc process developed by ABB in the 1990s for conversion in a DC furnace of fly ash and bottom ash materials into a relatively inert glassy slag and the off-gases of alkalis and volatile metals refined into products. A schematic of the AshArc process is shown in Figure 4.

Fly ash is usually very fine and has high concentrations of hazardous materials. The IPBM process can address both these issues. Where organic material is present, the presence of hazardous components in the off-gas is addressed by a CO afterburner and an air cooler. The resublimated metals are collected in a bag filter. The filter cake, a metal concentrate, can be recycled to the metallurgical industry. The flue gas is further cleaned to remove SO₂ and HCl.

The glassy residue has been tested and has been shown to satisfy the requirements of the cement industry and construction applications based on leaching requirements including the Swiss-TVA [21].

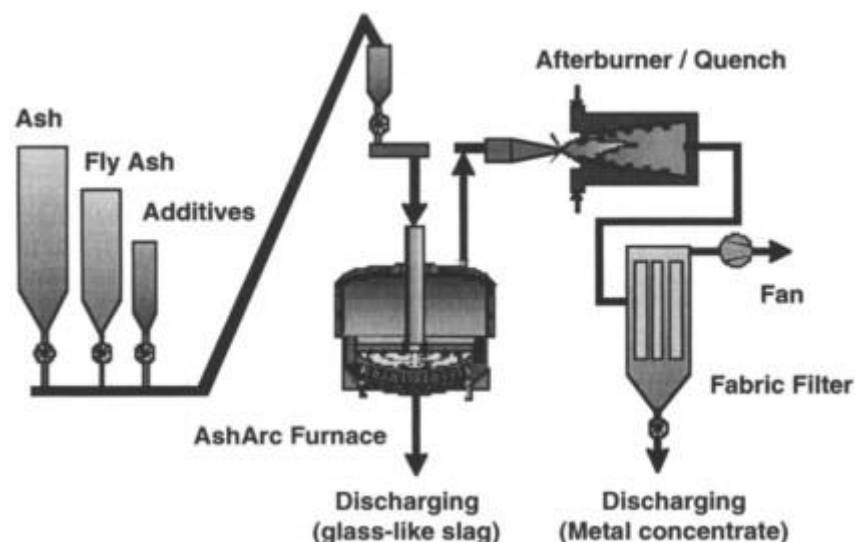


FIG. 4 AshArc Process

3.2.1.2 RecArc Process

As part of the EU Life Environment Demonstration Project (LIFE03 ENV/D/043), recycling of residues from metallurgical industry with arc furnace technology was investigated [22].

The project was a European Union funded collaboration between the Federal Institute for Material Research and Testing - BAM (Berlin) and FEhS – Institute for Building Material Research e.V. (Duisburg).

The goal of this project, entitled RECARC, was to completely recover the heavy metal fraction (principally chromium) of the slag resulting from the production of stainless steel and to convert the mineral fraction to a high-value building material. This was to be achieved by using an arc furnace.

The objectives of the project were threefold:

1. Demonstration on a technical scale of thermochemical treatment of residues (slags) from steel and stainless-steel production.
2. Production of a pure metallic fraction for recycling.
3. Production of a slag with low concentrations of heavy metals, so that the mineral fraction can be used as a building material.

The RecArc process is shown in Figure 5.

The slag charge material was melted in a 300 kW alternating current arc furnace under reducing conditions using graphite electrodes.

The project achieved a separation of the molten slag and a lower liquid metallic layer which sinks due to its higher density. Without the reducing agents the chromium and other metals stay within the slag layer. The carbon released from the graphite electrodes is insufficient to achieve any appreciable transfer of chromium to the metal layer. The addition of reducing agents such as carbon, aluminium or silicon reacts with the oxygen and releases the chromium which flows to the metallic layer.

Optimisation of the process was undertaken using different length arcs and resistance heating (graphite electrodes penetrating the molten surface layer) with and without reducing agents. The best separation efficiency of chromium was found with resistance heating where a 90% chromium recovery rate was achieved using pet coke (a light porous form of carbon) as the reductant.

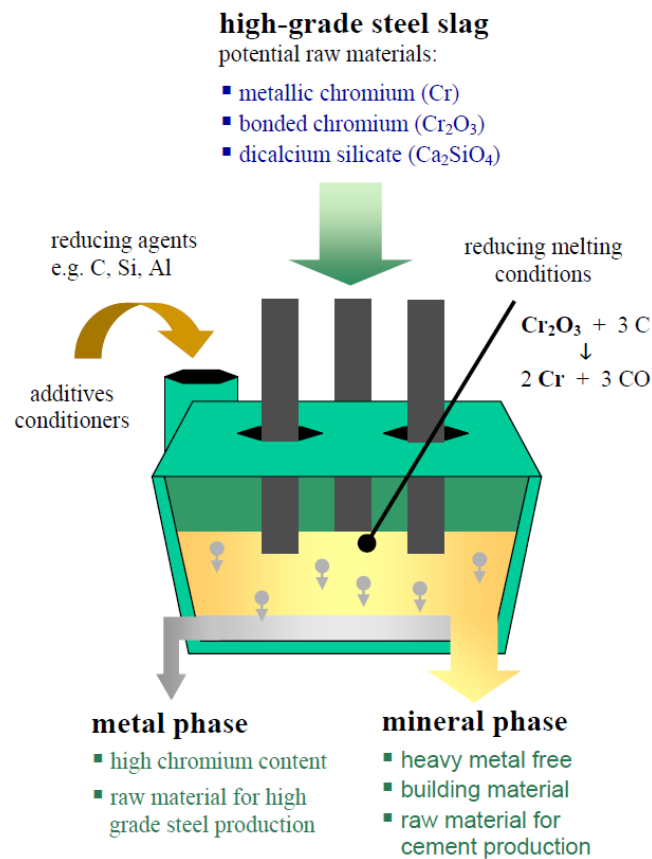


FIG. 5 Scheme of the RECARC Process

A high-quality slag product was achieved with 0.1% chromium which is below the 0.2% chromium level considered as the limiting concentration for application in the cement industry.

Optimisation of the slag by-product is achieved using silica and alumina before casting. To reduce leachability for the cement market, the slag by-product must contain sufficient quantity of silica to produce a glasslike or vitrified product on solidification.

The slag is granulated using rapid cooling through a swirled jet nozzle using water and air as shown in Figure 6. Pin-head sized pellets are produced to meet the market requirements of the cement industry.

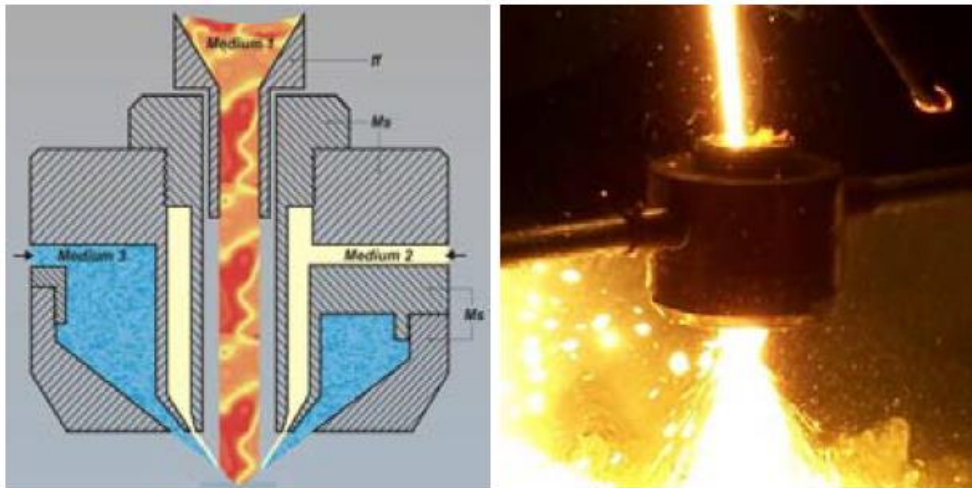


FIG. 6 Slag Granulation Head

The grades of slag by-product are shown in Figure 7 for both the construction industry and for the cement industry.



FIG. 7 Slag By-products - Construction (Left) Cement (Right)

The chromium rich metal product determines the economic viability of the process.

The RECARC process has demonstrated a high efficacy in the recovery of the charged material demonstrating its circular economy credentials. The metal phase elements of chromium, iron, manganese, vanadium, nickel, carbon and silicon in the alloy can be used directly as a raw material without subsequent processing. Halides, alkali metals, zinc and lead are removed in the off-gas.

The mineral content in the charge material also achieves a high recovery rate in the construction grade by-products produced. The addition of slag processing additives allows a granulated cement grade material. Heavy metal content is significantly reduced to an acceptable level for the cement

market. Vitrification of the slag by-product results in a reduction in the leaching of lime and other metal oxides resulting in a high-grade construction material.

3.2.1.3 Plasminox Process

An industrial example of the arc technology for carbothermic reduction of stainless-steel waste is the plasma arc furnace installed at ThyssenKrupp, Terni, Italy in 1992 to process 20,000 tonne per annum of waste material. This was undertaken by Harsco (Plasminox Project) using Tetronics DC plasma arc smelting for stainless steel EAF/Argon Oxygen Decarburization (AOD) dust. A similar, but smaller facility, is operated by Outokumpo, Sheffield. The dust is classified as a hazardous waste with a high disposal cost.

The charge and fluxing additions (lime, silica) are added via a 300 mm hollow cathode and creates a high temperature plasma-arc in a plasma forming gas (Argon or Nitrogen). The process uses 1.7 MWh/tonne dust operating at 7 MW and 20 kA. In addition to the metal alloy, a saleable construction trade product (Plasmarok) is also produced – a glass product.

The consumptions of reductant and fluxing agent is 270 kg coal, and 60 kg lime per tonne of EAF dust charge.

It is reported that the process has recovered in excess of US\$300M (2013) in material values [23].

In addition to EAF dust, the Tetronics DC plasma arc smelting technology has also been used for recycling electric vehicle batteries, catalysts converters and waste electrical equipment. The recovery rate of the valuable metals has been in excess of 95% for Ni, Co, Cu, Sn (to alloy), Mn (to slag) and Pb, Zn (to dust).

Examples of where the Tetronics DC plasma arc smelting technology has been used are shown in Table 5 [24].

TABLE 5

APPLICATIONS OF TETRONICS PLASMA-ARC SMELTING TECHNOLOGY

Location	Year	MW	Application
Extensive Supply			
Indian client	2017	0.5	Autocat, chemical cat
EZOCM (Russia)	2016	0.6	Autocat, chemical cat
Duncan Recycling (USA)	2016	0.6	Autocat
BlueOak (USA)	2015	1.3	E-waste
Heesung PM Tech x 3 (South Korea)	2005 to 2014	0.4 to 1.0	Autocat, chemical cat
Hensel Recycling (Germany)	2014	0.6	Autocat
Sino-Platinum (China)	2013	0.6	Autocat
Furuya Metals (Japan)	2013	0.6	Chemical cat
Solar Industries (Taiwan)	2012	0.6	Autocat, chemical cat, e-waste
PPUK, Swindon (UK)	2007	0.6	Autocat
EA Technology (UK)	1993	0.3	Asbestos
Outokumpu, Sheffield (UK)	1988	2.5	Stainless steel EAF/AOD dust
Multimetco (USA) x 2	1892, 1986	1.2, 0.8	Autocat, chemical cat
Specification & Reduced Supply			
Japan x 9 (various)	1991 to 2000	0.1 to 1.4	Ash melting
MSE Inc (USA)	1995	0.4	Vitrification
Harsco, Terni (Italy)	1991	7.0	Stainless steel EAF/AOD dust
Plazmet (USA)	1990	5.0	Zinc-containing wastes
IMS x 2, Nucor/Yamata (USA)	1989	2.0, 2.5	Carbon steel EAF dust
Presur (Spain)	1989	2.5	Chromite ore smelting
Built Under Licence			
Japan x 10 (MHI, Takuma)	1995 to 2005	0.8 to 4.0	Ash melting

3.2.2 Arc Smelting Cost-Benefit Assessment

The cost-benefit assessment for arc smelting processes is complex due to the large variability of potential material feedstocks and products.

Sometimes the economics are driven by considerations other than those of the materials that are being produced. For example, the Harsco operation at Terni, Italy was undertaken to ease a pressing operational constraint on the production of stainless steel due to the unavailability of on-site storage capacity for the EAF dust. As a hazardous material transportation off-site would have incurred a very high cost to the business.

The most significant factor in the cost-benefit assessment is the inherent value of the feed material and the amount of valuable metals that can be extracted to either a metal alloy product and/or an off-gas extract.

Some materials containing significant quantities of precious metals such as platinum, palladium and rhodium from catalytic converts provide an obvious incentive for economic recovery. The same is true of EAF dust which is rich in valuable metallics such as vanadium and nickel (recovered to alloy) and zinc (recovered to off-gas).

Unfortunately, the same is not true of other wastes such as blast furnace or basic oxygen steelmaking wastes unless other cost factors are considered. This is because the composition of valuable materials is normally relatively small as identified in the NWE-REGENERATIS report on metallurgical site deposit historical data for the PMSD Teesside site [1].

The most significant valuable metal concentration based on the historical data of the PMSD Teesside site is located in the Waste Management area and SLEMS. This is primarily the location of basic oxygen steelmaking dusts and sludges including oily millscale. However, the data indicates that the concentration of zinc is relatively small even though the absolute quantity is large. This is partly due to blast furnace dust and sludges also being deposited in this area and reducing the concentration of the valuable metals.

Another problem is that the BOS steelmaking dust and sludge deposits are intermingled with larger slag deposits, so that there is a cost of segregation and/or particle size reduction.

Also, over many years (pre-1970s), legacy coke oven gas processing plant liquid wastes and oily residues from the oil refinery entered the watercourses that fed the Waste Management and SLEMS areas. As a result, the ground materials are contaminated with organic and hydrocarbon pollutants. In several cases, this is at contamination level that classifies the waste as hazardous. This makes the remediation of this area of the site difficult and costly.

When the available technology options are considered for the PMSD Teesside site, both the rotary hearth furnace (RHF) and electric arc smelter are problematical. For viability, the RHF requires a feed stream of a higher zinc content – typically minimum 10% mass fraction. At this feed concentration, this provides a saleable crude zinc oxide (CZO) product for downstream refiners. At less than 5% mass fraction, the CZO achieves a much lower revenue stream. There is also the problem of BOS oxide contamination with organics and hydrocarbons. Because the processing temperature in the RHF is relatively low (800 °C), the contaminants could produce hazardous gaseous species (such as dioxin, furans) that would require a high temperature after-burner to safely dispose of these pollutants. This waste gas treatment process would add significantly to the cost of the RHF.

Electric arc smelting does have the capability to convert the organic and hydrocarbon pollutants to simpler, benign species such as CO and H (syngas species). In some waste processes (e.g. sewerage sludge) there is sufficient organic and hydrocarbon material present to produce enough syngas to support the power cost of running the plant. The power for operating an arc smelter is significant, typically 1.5-1.7 MWh/tonne charge, though this can be reduced where the waste is transferred to the smelter in molten form. For PMSD Teesside, this is not the case, so imposes a significant cost burden on the process economics.

Another factor of the arc smelter is that the process throughput of the reference sites is relatively small in comparison to the quantities of materials residing at PMSD Teesside. For example, the Harsco Terni plant annual throughput is only 22,000 tonne per annum compared to site deposits of an order of magnitude larger than this at the SLEMS alone. This means that the economics of processing the iron units is not viable and would be reliant on the zinc production. There is, therefore, a mismatch on the economies of scale between the technology and the market.

3.2.3 Future Arc Technology Strategy

Given the challenges of recovery of materials from the PMSD 1 Teesside site, a new approach is required to address the technical and economic barriers.

The guiding principles adopted are:

- Since the energy costs of recovery are heavily dictated by the high proportion of minerals (non-metallic content), the minerals have to be considered integral to the process and as potential marketable products. To this end technologies to enhance their value are necessary.
- Conversely, since the concentration of non-ferrous metallic species is relatively low in the PMSD 1 Teesside site material, the large power cost of electric furnaces requires concentration of the non-ferrous metallic species in the furnace charge material. Ferrous metals can be removed relatively easily from the slag by mechanical and magnetic separation, so this is a pre-requisite to smelting the non-ferrous materials. The ferrous materials can be processed to meet the established markets in the iron and steel industry.
- The non-metallic (mineral) content of the furnace charge material places a heavy burden on the power cost of the electric furnace, so it is necessary to remove as much of this as possible prior to melting. This can be undertaken using technologies such as eddy current separation to separate the metal conducting species.
- To maximise the revenue potential of furnace operation, recovery of the volatile metals is required in the form of a mixture of zinc and lead oxides. The crude zinc oxide (CZO) material would be sold to the CZO processes using hydrometallurgy and electrowinning to recovery pure zinc and a lead-based product.

Adopting the above guiding principles results in the integrated processing route outlined in Figure 8.

Crude Zinc Oxide (CZO) can be processed using hydrometallurgy and electrowinning to recover pure zinc.

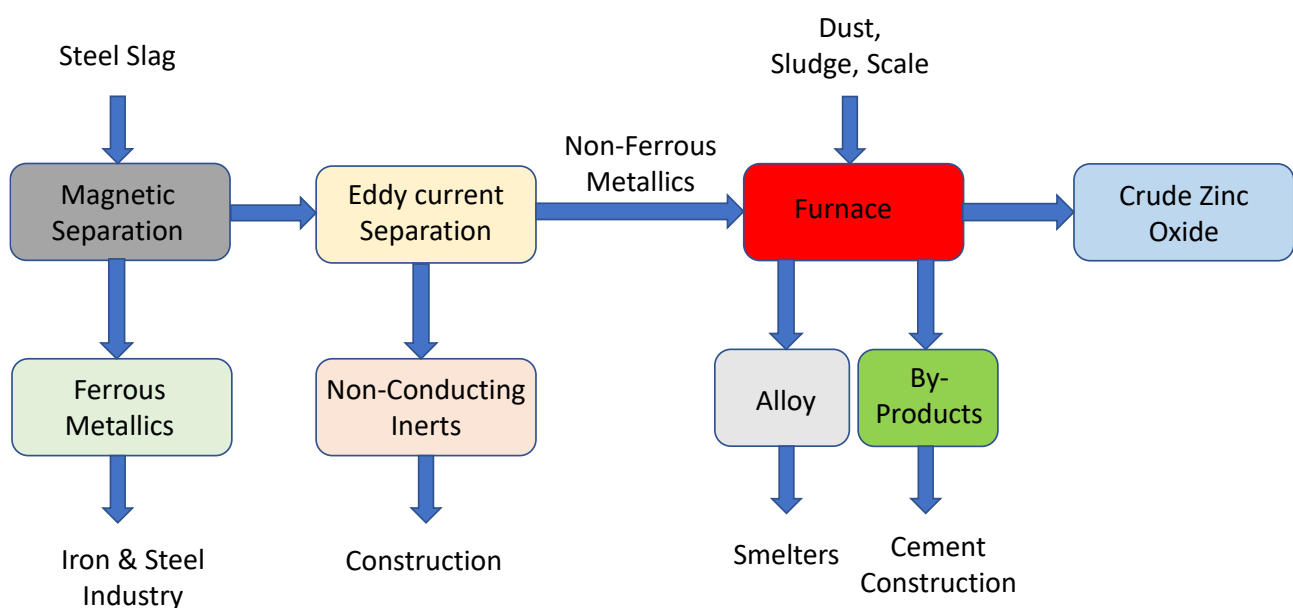


FIG. 8 Integrated Steel Waste Processing Scheme

To address the economic viability of this processing scheme, a process model is required. This is currently in development based on Microsoft Excel. To ensure that the model reflects realistic assumptions, the process model is being developed with external scrutiny from established operators in the iron and steel industry metal and mineral recycling industry.

Key elements of the Excel spreadsheet model are the calculation of the alloy, slag by-product and condensed volatile fractions compositions from the metal oxide composition of the furnace charge material and knowledge of the stable, reducible and condensed volatile oxides under furnace operating conditions. Perhaps the most significant issue to be addressed is the power overhead cost of the stable oxides such as calcium and silicon oxide.

Providing the Excel process model confirms the economic viability, it is proposed to develop a physics-based model description of the process in a suitable process modelling language. This will provide a framework to support characterisation and parameterisation of the transformation processes including the material and energy balances. The model will also allow optimisation of the process.

The significant challenges of an integrated steel waste processing plant are as follows:

- Meeting the iron and steel industry technical specification for the ferrous metallic products.
- Efficacy of eddy current separation for separation of the non-ferrous metallics. This is particularly challenging given that the oxides of the non-ferrous metals have low electrical conductivities due to their crystalline lattice structure.
- Meeting the construction industry required technical specification for construction materials.
- Further processing steps will be required following eddy current separation.
- Arc furnace optimisation and operation to achieve a high metal recovery rate.
- Off-gas cleaning and volatile metal recovery.
- Process operation decision making.

The process model will be used to support process operation decision making. A key element of this will be decision support on the additional furnace feed materials. For example, dusts, sludges and oily mill-scale could be used in addition to slag derived non-ferrous metals. Some of the dusts, sludges and oily mill-scale could be obtained from operational iron and steelmaking sites. This is likely to have both technical and commercial advantages over legacy wastes from PMSDs.

There is also the possibility of providing a processing route for metal processing industries outside the iron and steel sector. Arc technology is able to recover a broad range of metallic wastes including catalytic converters, industrial catalysts, fly ash and titania wastes.

4 REFERENCES

1. Capstick, M.A., Regeneratis Report: T1.1.1.1 Teesside Metallurgical Site Deposit Historical Activity Data, INST/LCE/R/28042/1/20/C, 29 June 2020
2. Ye, G., Burstrom, E., Kuln, M., Piret, J., Reduction of Steelmaking Slags for Recovery of Valuable Metals and Oxide Materials, Scandinavian Journal of Metallurgy, Vol 32, Issue 1, pp 7-14, Feb 2003
3. Zingaretti, D., Costa, G., and Baciocchi, R. Assessment of Accelerated Carbonation Processes for CO₂ Storage Using Alkaline Industrial Residues. Ind. Eng. Chem. Res. 53, 9311-9324. doi:10.1021/ie403692h, 2014
4. Sundermann, C.M., Production of Calcium Carbonate from Steelmaking Slag and Captured CO₂ – Optimisation of the Carbonation Process and Product Quality, Master Thesis, Aalto University, Finland and Royal Institute of Technology, Sweden, Nov 2016
5. Yu, Qi, Metal Recovery from Steelmaking Slag, Master Thesis, Department Materials Science and Engineering, University of Toronto, 2018
6. Private Communication, Harsco Environmental, December 2020
7. South Tees Regeneration Master Plan, South Tees Development Corporation, March 2019
8. Capstick, M.A., Paterson, C., Market Feasibility Study, INST/CP/R/10195/1/19/C, 31 January 2019
9. Payne, L M et al, Ferrous Waste Recovery from Corus' UK Sites, Corus Research, Development & Technology, August 2008.
10. DRI Reduction Process, <https://www.metallics.org/dri-production.html>, 31/01/2019
11. ISSB (International Steel Statistics Bureau), European Imports 2003-2017 Data
12. Midrex Stats Book 2017,
https://www.midrex.com/wpcontent/uploads/MidrexStatsBook2017.5_.24_.18_.pdf
31/01/2019.

13. DRI Reduction Process, <https://www.metallics.org/dri-production.html>
31/01/2019
14. <https://eurasiasteelservices.com/hot-briquetted-iron-directly-reduced-iron.html>
<https://ispatguru.com/iron-and-types-of-iron>
<https://www.metallics.org/hbi.html>
<https://www.metallics.org/dri.html>
all 31/01/2019
15. DK Recycling, <https://www.dk-duisburg.de/en/home/>
16. Ye, G. et al, Reduction of Steelmaking Slags for Recovery of Valuable Metals and Oxide Materials, Scandinavian J. of Metallurgy, 32, 7-14, 2003
17. Ye, G., Lindvall, M., Magnusson, M., Swerea MEFOS Perspective on Metal Recovery from Slags, Third Intl. Slag Valorisation Symposium, Leuven, Belgium, 19-20 March 2013
18. Lindvall, M., Ye, G., Experience of Using Metallurgical Reactors for Reduction of Vanadium Bearing Steel Slags and Other Wastes, Proceedings of International Smelting Technology Symposium, TMS 2012, 147-154, Orlando, Florida, USA, 11-15 March 2012
19. Lindvall, M., Ye, G., Karsrud, K. (ed), Presentations of the VILD Seminar 2012, Lulea, Sweden, 10-11 October 2012
20. Ogawa, Y., Yano, M., Kitamura, S., Hirata, S., Testsi-to-Hagane, 87, 21, 2001
21. TVA Technical Ordinance on Waste: http://www.admin.ch/ch/d/sr/c814_600.html
22. Recarc – Recycling of Residues from Metallurgical Industry with the Arc Furnace Technology, LIFE03 ENV/D/000043, 2003-2006
23. Deegan, D., Plasma Power, Technology and Innovation CIWM, Dec 2013
24. Johnson, T., Plasma Smelting: Techno-Economic Assessment Study Report, Tectronics International, 21 February 2019