Recovery Processes of Small and Powdered Iron-Containing Waste, from the Steel Industry

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Abstract: On a daily basis, within the steel industry, significant amounts of small and powdered waste are generated, which possess intrinsic value, determined by their content of useful elements (e.g., Fe, C). For this reason, there is a growing tendency to recover such waste, with the goal of reintroducing it into the technological processes where it originated, in the form of secondary raw materials. This paper presents a series of processes for the recovery of waste from the steel industry, developed and applied worldwide. The authors consider that, in Romania, the applicability of direct reduction processes for iron ores and/or small and powdered waste with high iron content, as presented in this paper, is limited. Through this paper, the authors aim to emphasize the importance and reliability of classical recovery processes for small and powdered waste with iron content (pelletizing, briquetting, agglomeration). To this end, they present a series of experimental studies as examples of good practices, aimed at reducing pollution caused by storing such waste in outdoor locations, either directly on the ground or in disused halls.

Keywords: steel industry; small and powdery waste containing iron; recovery processes; direct reduction processes

1 Introduction

A significant amount of industrial waste containing iron is generated and stored; therefore, efforts are made to exploit its useful content (Fe) and intrinsic value by processing the waste and subjecting the resulting products to temperatures below iron's melting point. This approach characterizes direct reduction processes, which involve converting iron ore and/or fine, powdered waste with high iron content into metallic iron in its solid state.

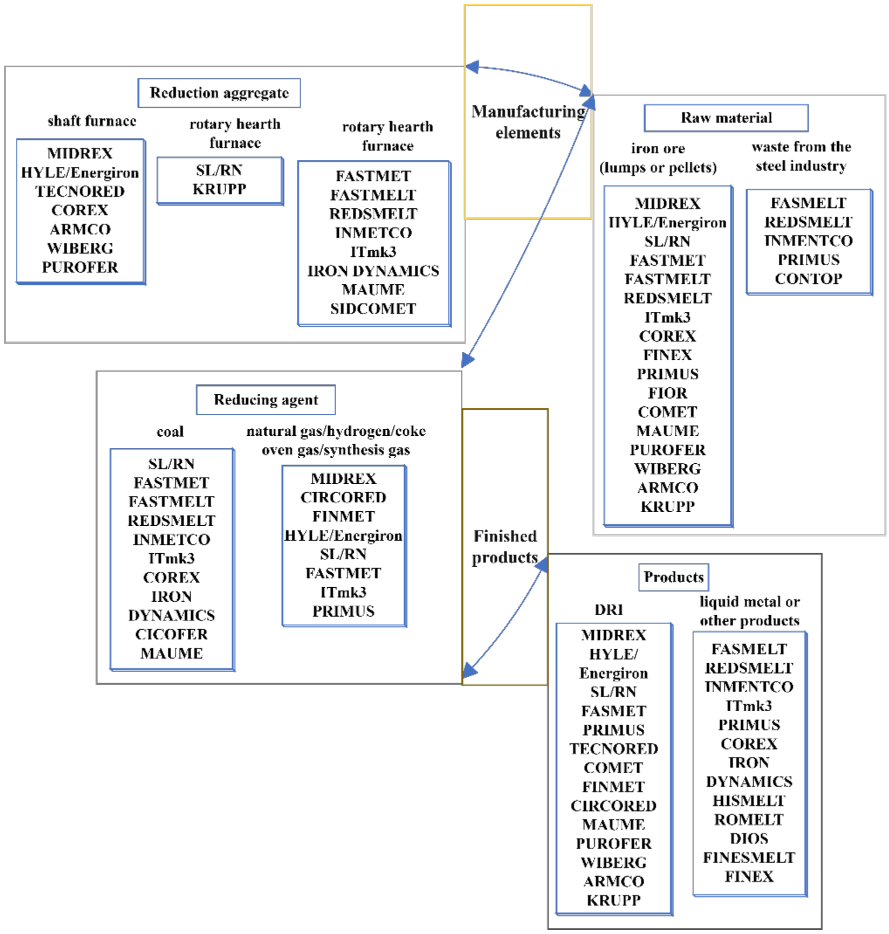
According to the literature [1-6], sponge iron, which can be produced in various forms, may be added to the charge of electric arc furnaces, induction furnaces, oxygen converters, or blast furnaces, provided the following chemical composition requirements are met:

- The iron content must be at least 90%
- The sum of the elements Al_2O_3, MgO must be a maximum of 2%
- The CaO/SiO_2 ratio has values in the range of 0.10-0.20
- Carbon content is usually less than 2%

Worldwide, direct reduction processes produce sponge iron, known as DRI (direct reduced iron) or CDRI (cold direct reduced iron), and HDRI (hot direct reduced iron), which is hot compacted through pressing and transformed into briquettes called HBI (hot briquetted iron) to facilitate handling, transport, and storage [3] [5].

In industry, as indicated in the literature [7-9], there are numerous direct reduction processes classified based on various criteria. Figure 1 illustrates the classification of direct reduction processes practiced worldwide, according to the most relevant criteria: the type of equipment used, the raw materials, the reducing agent, and the final product obtained.

It is important to note that the direct reduction processes for iron ores and/or steel industry waste, practiced globally and presented below, are not implemented in Romania. The possibilities for their applicability are very limited due to the lack of necessary infrastructure and funding. Consequently, classical processes such as pelletizing, briquetting, and agglomeration remain in use.



Classification of direct reduction processes that occur in industrial practice

2 Methodology

The methodology for this study begins with an extensive analysis of the most well-known, direct reduction procedures applied to iron ores and/or fine, powdered waste with high iron content, resulting in sponge iron in the form of CDRI, HDRI and HBI.

Classical processes for recovering fine and powdered waste with iron content (pelletizing, briquetting, agglomeration) can be considered viable alternatives to the processes summarized in Figure 1, particularly in the context of the Romanian steel industry. Therefore, in the second part of the article, the authors present a series of experimental studies conducted in the laboratories of the Faculty of Engineering Hunedoara, Politehnica University of Timisoara. The research results provide practical solutions for recycling fine and powdered waste with high iron content, which is either historically stored or still generated in manufacturing flows within the industrial area of Hunedoara.

2.1 Iron Sponge Manufacturing Processes from Ores and/or Small and Powdery Waste with a High Iron Content

2.1.1 FASTMET Process

As part of the direct reduction process, iron ores and/or steel mill waste (fine and powdered waste containing iron) are converted into sponge iron in a rotary hearth furnace reduction plant, using carbon (coke or high-carbon waste) as the reducing agent [9-12].

The current FASTMET technology was originally developed in 1965 by the Midland Ross Corporation, National Steel Corporation, and Hanna Mining [9, 11, 12]. A demonstration plant for the FASTMET process was constructed in 1995 at Kobe Steel's Kakogawa Works [9, 11, 13].

At present, the installed capacity of the six DRI plants utilizing FASTMET technology ranges from 16000 to 190000 tons per year, as detailed in Table 1.

The primary fine and powdered waste materials that can be processed (to recover their zinc content) and recycled using the FASTMET process include blast furnace dust and sludge, converter dust, sinter dust, steelwork dust, mill scale, and mill scale sludge [12].

Table 1

Plant production capacities using FASTMET technology [11, 13]

Plants and owners	Processing capacity, [t/year]
Nippon Steel & Sumitomo Metal (Hirohata Works)	190000
Kobe Steel, Ltd. (Kakogawa Works)	16000
Nippon Steel & Sumitomo Metal (Hirohata Works No.2)	190000
Nippon Steel & Sumitomo Metal (Hirohata Works No.3)	190000
JFE (Fukuyama Works)	190000
Kobe Steel, Ltd. J/V with NSSM (Nittetsu Shinko Metal Refine)	190000

The sponge iron produced through the FASTMET process can, similar to the previously described processes, be hot briquetted (HBI), hot discharged (HDRI), or cooled (CDRI) before being directly loaded into processing equipment such as furnaces, converters, or electric arc furnaces) [7, 10, 12].

The reduction process within the FASTMET plant (rotary hearth furnace) typically takes between 6 to 12 minutes, with the processing time directly influenced by the size of the material being processed [7] [10].

Given the environmental challenges faced by the steel industry—such as the depletion of raw material resources and the need to reduce CO_2 emissions—it is anticipated that the adoption of the FASTMET process will increase in the future among large steel plants [13].

In conclusion, steel industry waste is well-suited for recycling on a commercial scale using the FASTMET process, which has proven to efficiently recycle waste containing Fe and Zn. Therefore, this process offers a viable solution for valorizing iron-containing waste, both historically stored and generated by current production flows.

2.1.2 FASTMELT Process

This process builds on the same technology as the FASTMET process, with the addition of a melting furnace for producing hot metal, resulting in the FASTMELT process. Through FASTMELT technology, sponge iron produced via the FASTMET process is transformed into high-quality hot metal, known as FASTIRON [7, 9-12, 14].

The FASTMELT process was developed in 1995 by Kobe Steel in collaboration with Midrex Technologies as an alternative to the FASTMET process. It enables the production of cast iron, with sponge iron transformed into liquid metal, which can subsequently be loaded into blast furnaces or oxygen converters [10-12, 15, 16].

As with the FASTMET process, the raw materials used in FASTMELT are by-products (e.g., blast furnace dust and sludge, converter dust, steelwork dust) generated by steel plants, with carbon serving as the reducing agent. A key objective, as in FASTMET, is the recovery of Zn content from the waste.

After the reduction process is completed, the sponge iron (in pellet or briquette form) is discharged hot into an electric melting furnace, where sulfur is removed and slag is separated [11] [14].

The FASTMELT process produces FASTIRON, which serves as a clean metal charge for electric arc furnaces, offering several benefits, including increased productivity, consistent and high-quality steel production, and the ability to utilize greater amounts of lower-quality waste. The percentage of molten FASTMELT metal used in blast furnace loads is typically at least 15% and can exceed 30%. FASTIRON is also suitable for use in oxygen converters [12].

Processing steel plant waste through the FASTMET and FASTMELT processes minimizes the amount of iron-containing waste deposited, reintroduces waste into the economic circuit as DRI (used in the processes where it originated), and reduces fuel (coke) and electricity consumption.

Both processes are environmentally friendly. The only by-products generated are slag (with a composition similar to slag from steelmaking processes, which can be recovered in the same way) and ash (recoverable due to its ZnO content) [10].

2.1.3 INMETCO Process

The INMETCO process, developed by the International Metals Reclamation Company, involves reducing pellets made from various steel industry by-products (waste containing Fe and C) in a rotary hearth furnace to produce sponge iron, which is then hot charged into an electric arc furnace (EAF) to obtain liquid metal [8, 10, 12].

This process enables the recovery of a wide range of steel industry waste, including coal and coke dust, sinter dust and sludge, steel mill dust and sludge, scale, and mill scale sludge [10] [17].

Through the INMETCO process, based on high-temperature metal recovery technology, chemical elements such as Fe, Ni, Cr, Mo, and Co are recovered from the aforementioned steel by-products and used for the production of Fe-C alloys (cast iron, steel) [18] [19].

High-temperature metal recovery technology is a process that uses physical or chemical methods to recover heat-resistant metals from slag, ash, and other materials. The process involves the following four steps [10] [18]:

- Preparation of materials (classification, dosing) for the manufacture of raw pellets
- Reduction of raw pellets in the rotary hearth furnace and the obtaining of the iron sponge
- Melting of the iron sponge in melting aggregates (electric arc furnace)
- Casting of molten metal

In essence, the effectiveness of this process is demonstrated not only by the ability to reintroduce steel waste into manufacturing streams and produce a new product, but also by the recovery of significant amounts of Zn and Pb from the dust generated during the production of sponge iron [10]. These recovered metals are subsequently used in the non-ferrous metal industry as additives.

2.1.4 REDSMELT Process

The process developed by Paul Wurth emerged from the combination of two industrially proven technologies. In essence, the REDSMELT process utilizes coal-based reduction technology to treat raw pellets in a rotary hearth furnace (the same technology as the INMETCO process), as well as the technology for melting the produced sponge iron in a submerged arc furnace to obtain liquid metal [12, 20-26].

Various iron-containing wastes, mainly from the steel industry, can be recovered through the REDSMELT process, including fine and powdered waste.

The REDSMELT process involves three phases: the manufacture of raw pellets, the reduction of these pellets in a rotary hearth furnace, and the melting of the resulting sponge iron in a submerged arc furnace [10, 12, 23]. Figure 2 illustrates the concept behind the REDSMELT process, based on the reference study [9] [12].

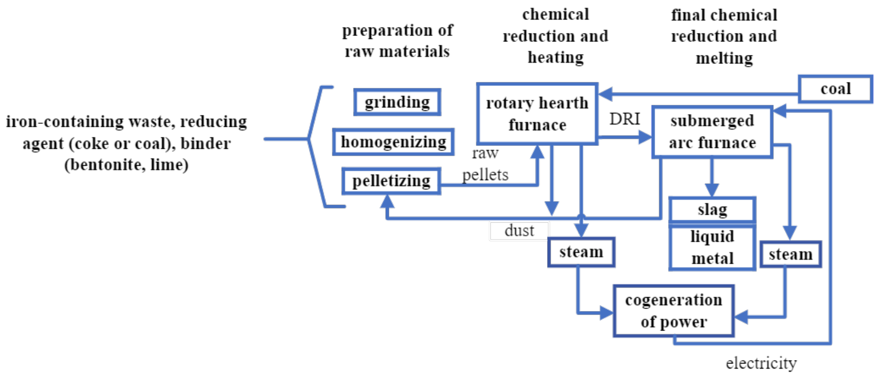


Figure 2
The concept of REDSMELT technology

Within the technological flow of the REDSMELT process, nearly all by-products (especially sludges and dusts) generated during various steel plant processes (blast furnace, electric arc furnace, oxygen converter) can be recovered [21-23].

The hot DRI product, resulting from the reduction of the pellets, is loaded into the submerged arc furnace for melting, producing hot metal (which can be used in steel and cast-iron manufacturing) and slag [23] [24].

The application of the REDSMELT process represents an optimal solution for minimizing the quantities of fine and powdered iron-containing waste that have been historically and frequently deposited. The proposed technology is simple and reliable for hot metal production, with capacities, investments, and operating costs that are advantageous. Notably, no electricity is required, as the melting of the DRI is carried out using chemical energy. The system has high productivity, which results in limited investment costs, making it suitable for mini-plants or steel mills where the production is based on supplying liquid cast iron from the blast furnace sector.

2.1.5 PRIMUS Process

The technology of this process, developed by Paul Wurth S. A., involves the treatment of waste generated by the steel industry (such as sludges, steelwork dust, scale, etc.), by applying a process that separates the Zn and Pb content from the ferrous fraction of the waste. This ferrous fraction is recovered through the direct reduction process and transformed into sponge iron [22, 25, 26].

The main equipment used in the PRIMUS process is the tiered furnace, which functions both as a drying unit and a reduction furnace. The tiered furnace has a cylindrical structure, with its interior divided into overlapping floors, each containing fixed hearths. Gaps between the hearths allow the material to pass from one floor to the next. The furnace is heated using burners installed on its outer walls [12] [13].

The tiered furnace, in terms of its operational mode, is considered the most suitable equipment for the thermal processing of small materials. Coal is also used as the reducing agent in this process.

The degree of Zn and Pb recovery from steel waste through the PRIMUS process exceeds 95%, and the recovered quantities are used in the non-ferrous materials industry [26].

In conclusion, the PRIMUS process provides high-quality sponge iron by processing fine, powdery waste and injecting coal as the primary energy source.

2.2 Experiments regarding the Recovery of Ferrous sludges Generated within the Steel Industry using Classical Capitalization Processes

In Romania, the application and implementation of a direct reduction process for ores in a steel plant is not currently of interest, as the necessary investments would be substantial. Moreover, for any of the aforementioned processes, adaptations would be required based on current research, development, and innovation conditions, as well as the activities of the plants, and the evolving state of iron ore markets (since ore reserves are being depleted).

It is important to note that steel companies are concerned and interested in recovering by-products (fine and powdery waste containing iron) generated by using classical waste processing/recovery methods (pelletizing, briquetting, agglomeration), which are applied worldwide. Therefore, a series of experimental investigations carried out under laboratory conditions is presented below.

Small ferrous waste originates from steel processes (steel mill slag and the ferrous fraction of steelwork), and from the mining industry (specifically, the preparation of siderite ores, i.e., ferrous concentrate from siderite waste) [27] [28]. Depending on the processes used, the waste may be presented in a dry or wet state (as sludge), and its preparation for reuse varies accordingly.

This waste is generated in the current production flows of ferrous semifinished products in significant quantities across the country (predominantly in the western part). Additionally, there are numerous historical landfills of industrial waste with high iron content (in locations such as Hunedoara, Reșița, Turnu Măgurele, Făgăraș, Oradea, etc.) [29].

For the experimental research conducted, the following materials were used: mill scale sludge, ferrous sludge, and agglomeration sludge. The granulometric composition was determined using a "Fritsch Analysette 3 Spartan sieving device", which features seven granulometric classes and sieves with mesh sizes ranging from 50 to 1000 µm. The results obtained are shown in Figure 3.

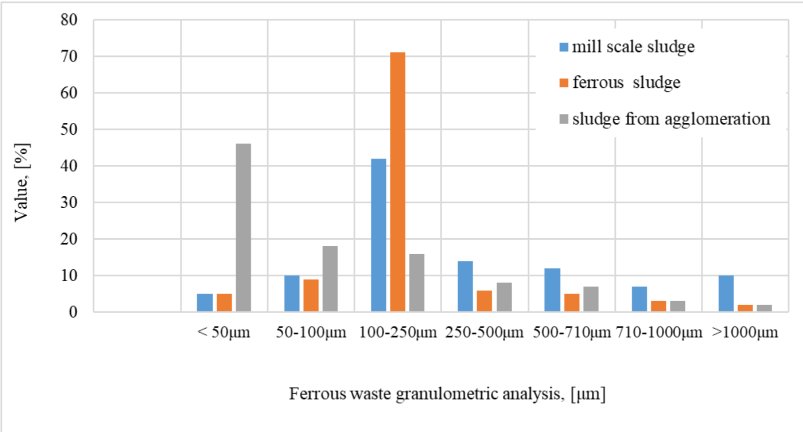


Figure 3
Particle size analysis of waste used in the experiments

From the analysis of the particle size of the waste, it was found that the fractions below 500 µm ranged from 71% for mill scale sludge to 90% for ferrous sludge, respectively. The coarse fraction, over 1000 µm, ranged from 2% to 10% (for agglomeration sludge). This granulometric distribution makes the studied waste suitable for processing through pelletizing, briquetting, and agglomeration.

In the decision-making process regarding the choice of recovery technology, the following factors must be taken into account: the characteristics of the waste, the destination of the finished product, and the existing processing facilities. These aspects were considered in the experiments carried out and presented in this paper. Following the experiments (processing the sludges through the classical methods - pelletizing, briquetting, and agglomeration), the results and products obtained are presented below.

2.2.1 Processing by Pelletizing

The processing of small and powdery waste through pelletizing involves the formation of spheres in their raw state by rolling a mixture of waste, binder (such as cement or bentonite), and a quantity of water in a pelletizing unit [27-30].

Figure 4 schematically illustrates the pelletizing process, carried out after reviewing the references [27-31].

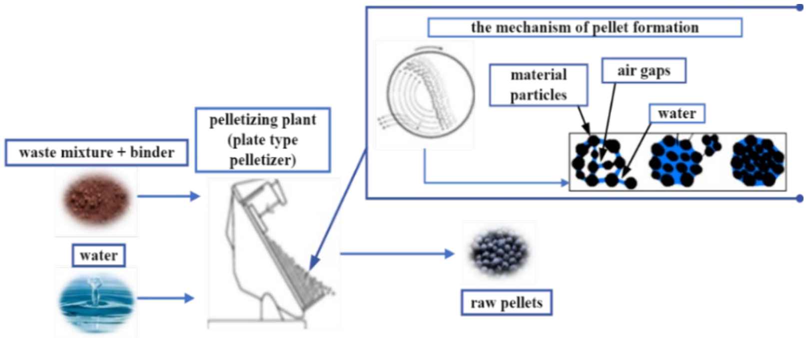


Figure 4
The process of pelletizing small and powdered waste

The experimental technology and the working phases for processing ferrous waste by pelletizing were as follows: preparation of ferrous sludges in powder form (ferrous sludge, mill scale sludge, agglomeration sludge) for the formation of the mechanical mixture; determination of the chemical and granulometric composition of the group of materials to be processed; dosing of materials according to the established recipe; homogenization of the materials; pelletizing of the mechanical mixture; hardening of the raw pellets (Figure 5); and determination of quality characteristics.

Figure 5
The aspect of iron pellets made of sludge waste

Following the pelletization process, pellets and micro-pellets were produced, which were subsequently reduced in the furnace at temperatures of 1250-1300°C. These temperatures allowed for the formation of an amorphous product, which can be assimilated as iron sponge.

2.2.2 Processing by Briquetting

The process of recycling small and powdery waste through briquetting involves pressing the mixture formed from the waste and binder into larger pieces with shapes such as oval, spherical, parallelepiped, etc. (the shape is determined by the mold in which the material/mixture is pressed) [29].

The experimental technology and the working phases for processing ferrous waste by briquetting are the same as in the case of pelletizing, with hydraulic presses being used for the installations. Images of the hydraulic piston presses used, as well as the briquettes that were subsequently heat-hardened, are shown in Figure 6.

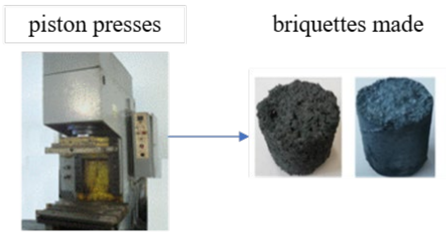


Figure 6
Making briquettes from sludge waste

By briquetting the mentioned waste and subsequently hot-hardening the resulting briquettes, pre-reduced (metallized) briquettes were obtained, which can also replace sponge iron in the load of processing aggregates (for cast iron or steel)).

2.2.3 Processing by Agglomeration

The agglomeration process, considered one of the most widely used methods to recover waste from the steel industry, involves exposing the waste to high temperatures. This physico-chemical process also results in an increase in the content of useful elements (in this case, iron) by removing compounds and volatile elements (such as S, CO_2, As) [10, 28, 30].

The experimental technology and the working phases for processing ferrous waste by agglomeration are the same as those for pelletizing and briquetting, with the equipment used being the agglomeration drum.

The appearance of the ferrous agglomerate obtained from the processing of sludge-type waste is shown in Figure 7.

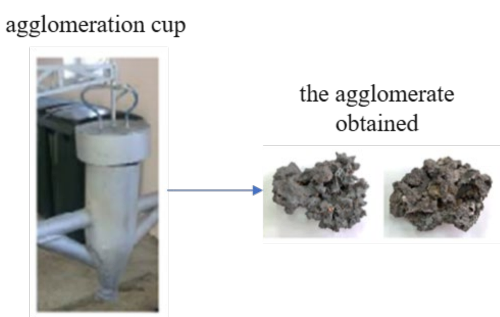


Figure 7
Aspects regarding the agglomeration process

To achieve the practical agglomeration of the studied waste, a preliminary stage was undertaken: increasing the size of the ferrous materials by pelletizing (since the initial dimensions of the waste risked preventing the proper functioning of the agglomeration equipment). The agglomerate, along with the by-products presented previously, can be used in the steel industry as a secondary raw material.

The secondary products obtained (pellets, briquettes, and agglomerate) are subject to handling and transport operations in industrial practice. Therefore, it is necessary for them to have a certain resistance during these operations; settlement or disintegration of these products would lead to non-compliance with the processing conditions needed to extract the iron.

The experimental by-products, presented in Figures 5, 6, and 7, were subjected to morphological and microscopic EDS analyses, which revealed a Fe content in the range of 52-78%.

These by-products are intended to be used as raw materials in the production of steel in electric arc furnaces, making it necessary to intensify the valorization of these wastes for economic, technological, and environmental reasons.

Following the experimental research, and based on aspects from the specialized literature [30, 32, 33], the secondary products obtained from ferrous sludges can be incorporated into the charge of the electric arc furnace to produce steel.

In this context, in the second part of the experimental approach, the agglomerate obtained under laboratory conditions was used as a raw material for steel production in the induction furnace (Figure 8). For the formation of the metal bath, steel waste was used, amounting to 4.5 kg of charge, and 3.5 kg of agglomerated material/charge. To correct the chemical composition, the following additions were made: 0.30 kg of lime/charge, 0.15 kg of bentonite/charge, 0.15 kg of fluoride/charge, and 0.20 kg of graphite/charge. The obtained steel sample was weighed, together with the extracted slag, to calculate the material balance. Based on the chemical compositions of the steel and slag, the recovery degree of the iron was determined. Tables 2-6 present the results obtained.

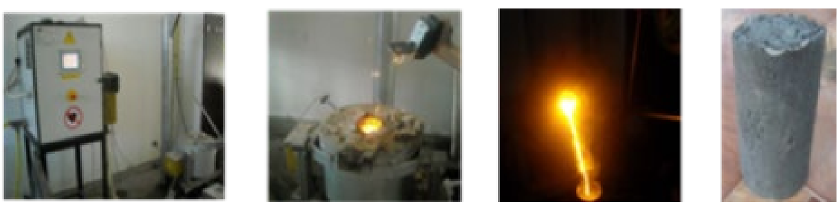


Figure 8

Aspects during steelmaking and casting in laboratory conditions

The degree of iron recovery from the agglomerate was determined using the formula:

$$\eta_{rec.Fe} = \frac{\%Fe_2 - \%Fe_1}{\%Fe_{agl}} \cdot 100, [\%] \quad (1)$$

where: $\eta_{rec.Fe}$ is the degree of iron recovery from the agglomerate, [%]

Fe_1 - the quantity of steel iron before agglomerate addition, [%]

Fe_2 - the quantity of steel iron after agglomerate addition, [%]

Fe_{agl}- the quantity of iron in the agglomerate, [%]

Table 2

Chemical composition of steel scrap

Chemical composition, [%]					
C	Mn	Si	P	S	Fe
0.44	0.68	0.29	0.031	0.032	98.514

Table 3

The final chemical composition of steel

Chemical composition, [%]					
C	Mn	Si	P	S	Fe
0.45	0.71	0.28	0.038	0.034	97.96

Table 4

The chemical composition of slag

Chemical composition, [%]									
CaO	SiO_2	Al_2O_3	MgO	CaF_2	FeO	MnO	P_2O_5	S	CaO/SiO_2
51.79	21.54	8.41	7.08	4.87	2.22	0.83	2.14	1.11	2.21

Table 5

Charging balance

Charge, [kg]				**Melt, [kg]**			**Gas dust, [kg]**
Steel waste	**Experimentally agglomerate**	**Addition materials**	**Total**	**Steel**	**Slag**	**Total**	
4.52	3.51	0.70	8.73	7.10	1.41	7.68	0.22

Table 6

Iron balance

Iron, [kg]					**$\eta_{rec.Fe}$ [%]**
Fe_1	**Fe_2**	**$Fe_2 – Fe_1$**	**Fe_{agl}**	**Fe_{slag}**	
4.36	6.95	2.59	2.62	0.024	98.85

From the data presented above, it follows, that the experimental agglomerate produced from pulverulent waste containing iron can achieve a high degree of metallization, making it suitable for use as a component in the charge of furnaces for steelmaking.

Conclusions

Taking into account the challenges faced by the steel industry, such as environmental pollution, depletion of primary raw material resources and the need to reduce CO2 emissions, the use of direct reduction processes, particularly those applied to small and powdery waste with iron content, will become a key component of steel companies' activities. These processes, as detailed in this work, provide solutions for recovering historically deposited iron-containing waste and that generated from current manufacturing flows, with the goal of reintegrating this waste into the production of Fe-C alloys.

Certain direct reduction processes, such as Primus, INMETCO, FASTMET and FASTMELT, focus on the recovery of Zn and Pb from the waste before the actual processing. This is a critical step, as these elements negatively affect the quality of metal products. This recovery effort is also present in the classic valorization processes (pelletizing, briquetting, agglomeration), aiming to enhance the quality of the final product.

Implementing a direct reduction process for small and powdered waste with iron content in a plant or steel company in Romania requires significant investment, alongside the continuous evaluation of the waste generated and deposited, as well as market trends. Steel companies that specialize in industrial waste recovery often opt for traditional recovery processes (pelletizing, briquetting, agglomeration), with a particular focus on briquetting. This is because briquettes, being larger and more robust, offer better handling and transport resistance, although they incur much higher costs compared to other methods.

The experimental research presented in this paper highlights feasible solutions for processing small and powdery waste. The preliminary results suggest new research directions that can lead to simple, efficient and cost-effective technological solutions for industrial applications. The products obtained, including pellets or micro-pellets, briquettes or agglomerates, demonstrate a high degree of metallization (over 95%), making them suitable for use in steel processing aggregates. Depending on the availability of waste, processors can adjust the composition of by-product recipes and processing technologies.

Furthermore, this research can be expanded to offer technological solutions for non-ferrous metallurgy.

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References

[1] E. Matei, A. M. Predescu, A. A. Șăulean, M. Râpă, M. G. Sohaciu, G. Coman, A. C. Berbecaru, C. Predescu, D. Vâju, G. Vlad, Ferrous industrial

wastes—valuable resources for water and wastewater decontamination, International Journal of Environmental Research and Public Health, Volume 19, Issue 21, 2022, pp. 1-25

[2] European Commission, Integrated pollution prevention and control (IPPC) - Best available techniques reference document on the production of iron and steel, December 2001, viewed at https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-03/superseded_is_bref_1201.pdf (accessed: 20.02.2023)

[3] A. Chatterjee, Sponge iron production by direct reduction of iron oxide, PHI Learning Private Limited New Delhi Publishing House, 2010

[4] C. D. Păcurar, Analysis of the EAF metal charge structure, Acta Technica Corviniensis - Bulletin of Engineering Hunedoara, Volume 8, No. 2, 2015, pp. 93-97

[5] M. Atsushi, H. Uemura, T. Sakaguchi, MIDREX processes, KOBELCO Technology Review, No. 29, 2010, pp. 50-57

[6] M. A. Elkader, A. Fathy, M. Eissa, S. Shama, Effect of direct reduced iron proportion in metallic charge on technological parameters of EAF steelmaking process, International Journal of Science and Research (IJSR), Volume 5, Issue 2, 2016, pp. 2016-2024

[7] O. Lupu, A. Socalici, E. Popa, O. Gaianu, Processing of ferrous iron and steel waste in the context of the circular economy, Journal of Physics: Conference Series, Volume 1781, 2021, pp. 1-8

[8] K. Meijer, C. Zeilstra, C. Teerhuis, M. Ouwehand, J. Stel, Developments in alternative ironmaking, Transactions of the Indian Institute of Metals, Volume 66, 2013, pp. 475-481

[9] C. Stănăşilă, N. Constantin, O. Stănăşilă, R. Petrache, Alternative iron making technologies, U. P. B. Sci. Bull., Series B, Volume 70, No. 1, 2008, pp. 56-62

[10] A. Socalici, E. Popa, T. Heput, F. Dragoi, Researches regarding the improvement of the steel quality, Solid State Phenomena, Volume 216, 2014, pp. 273-278

[11] A. M. Ghosh, N. Vasudevan, S. Kumar, Energy-efficient technology options for direct reduction of iron process (Sponge Iron Plants), The Energy and Resources Institute, 2021, pp. 1-67

[12] M. Kekkonen, L. Holappa, Comparison of different coal based direct reduction processes, Distribution: Helsinki University of Technology, 2000, pp. 1-44

[13] H. Tsutsumi, S. Yoshida, M. Tetsumoto, Features of FASTMET Process, Kobelco Technology Review, No. 29, 2010, pp. 85-92

[14] H. Ishikawa, J. Kopfle, J. Mcclelland, J. Ripke, Rotary hearth furnace technologies for iron ore and recycling applications, Archives of Merallurgy and Materials, Volume 53, Issue 2, 2008, pp. 542-545

[15] H. Tang, X. Fu, Y. Qin, T. Qi, Iron recovery and phosphorus removal from oolitic high-phosphorus haematite using the FASTMELT process: a comparative study of two reductants, Journal of the Southern African Institute of Mining and Metallurgy, Volume 117, 2017, pp. 387-395

[16] H. Michishita, H. Tanaka, Prospects for coal-based direct reduction process, Kobelco Technology Review, No. 29, 2010, pp. 69-76

[17] R. H. Hanewald, W. A. Munson, D. L. Schweyer, Processing EAF dusts and other nickel-chromium waste materials pyrometallurgically at INMETCO, Mining, Metallurgy & Exploration, Volume 9, 1992, pp. 169-173

[18] Cc. Yang, J. Pan, Dq. Zhu, Zq. Guo, Xm. Li, Pyrometallurgical recycling of stainless steel pickling sludge: A review, Journal of Iron and Steel Research International, Volume 26, 2019, pp. 547-557

[19] S. E. Logan, Risk assessment of alternatives for disposition of baghouse dust contaminated with cesium-137, Prepared for INMETCO The International Metals Reclamation Company, Inc. 245 Portersville Road Ellwood City, PA 16117, December 1997, pp. 1-46

[20] G. Cavallo, A. Chiappero, H. Lehmkuhler, REDSMELT: a friendly ironmaking process for minimills, Rev. Met. Paris, Volume 96, No. 3, 1999, pp. 341-348

[21] R. Degel, O. Metelmann, REDSMELT - an environmentally friendly ironmaking process, Steel Times International, Volume 24, Issue 2, 2000, pp. 30-33

[22] J. Rieger, J. Schenk, Residual processing in the European Steel Industry: A technological overview, Journal of Sustainable Metallurgy, Volume 5, 2019, pp. 295-309

[23] S. K. Dutta, R. Sah, Alternate Methods of ironmaking - Direct reduction and smelting reduction processes, S. Chand & Co Ltd, New Delhi Publishing House, 2012

[24] S. K. Dutta, Y. B. Chokshi, Smelting reduction processes - Basic concepts of iron and steel making, Springer, 2020

[25] M. Gojic, S. Kozuh, Development of direct reduction processes and smelting reduction processes for the steel production, Development of reduction processes for the steel production, Kem. Ind., Volume 55, Issue 1, 2006, pp. 1-10

[26] R. Frieden, T. Hansmann, J. L. Roth, M. Solvi, R. Engel, PRIMUS, a new process for the recycling of steelmaking by-products and the prereduction of iron ore, PAUL WURTH, 2001 pp. 1-12

[27] S. G. Șerban, I. Kiss, Identifying the possibilities for superior recovery by pelletization of industry related small and powdery iron containing waste, Acta Polytechnica Hungarica Volume 18, No. 4, 2021, pp. 79-104

[28] S. G. Șerban, I. Kiss, Superior recovery by pelletization of landfilled industry and mining related fine and small size iron containing waste, Acta Polytechnica Hungarica Volume. 18, No. 6, 2021, pp. 233-256

[29] D. A. Popescu, T. Heput, V. Puţan, Optimisation of the steel plant dust recycling process, International Conference on Numerical Analysis and Applied Mathematics (ICNAAM), AIP Conference Proceedings, Volume 1738, Issue 1, 2015

[30] N. Constantin, A. V. Socalici, R. Buzduga, A. C. Mihaiu, C. Dobrescu, O. N. Stanasila, E. F. Plopeanu, E. M. Vlad, Experimental research on a semi-industrial pilot scale for obtaining carbofer pellets in rotary tubular furnace, UPB Sci. Bull. Ser. B Chem. Mater. Sci., Volume 83, 2021, pp. 156-164

[31] O. Lupu, M. Ardelean, A. Socalici, E. Ardelean, Research regarding the capitalization of the waste resulted from the steel industry, U. P. B. Sci. Bull., Series B, Volume 83, Issue 1, 2021, pp. 188-196

[32] O. Lupu, L. Zgripcea, A. Socalici, E. Popa, C. Hărău, Pulverous ferrous waste processing by agglomeration, IOP Conference Series: Materials Science and Engineering, Volume 477, International Conference on Applied Sciences, 9-11 May 2018, Banja Luke, Bosnia and Herzegovina, pp. 1-8

[33] L. Xiaolong, P. Zhiwei, Y. Jiaxing, L. Zhizhong, H. Jiann-Yang, G. Yuanbo Zhanga, J. Lia Tao, Pyrometallurgical recycling of electric arc furnace dust, Journal of Cleaner production, Volume 149, 2017, pp. 1079-1100