THESIS TITLE

Doctoral Thesis – Resume

for obtaining the scientific title of doctor at
Polytechnic University of Timișoara
in the doctoral field Materials engineering

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PREFACE

Steel has a decisive role on the sustainability of our society by implementing the circular economy, by adopting and fully addressing the life cycle of materials, which measures the social impact, economic and environmental of a semi-finished product. The steel industry is an integral part of the circular economy model, promotes the concept of zero waste and reuses and recycles materials. The circular economy leads to optimal resource efficiency and semi-finished products and finished products are designed to be sustainable, easy to repair and recyclable.

The research carried out during the doctoral thesis was aimed at expanding the base of raw materials and materials in the steel industry by obtaining iron-containing by-products and their reintroduction into the circuit of steel production with technological, economic and ecological advantages. Methods and technologies for recycling and recovery in the form of briquettes, agglomerates or pellets of small and powdered waste containing iron have been identified, with the possibility of easy implementation in industrial practice, with relatively low costs by waste processing companies. This doctoral thesis presents the experimental research and the results obtained regarding the possibilities of capitalizing on small and powdered wastes containing iron in the steel industry. The experimental research in the laboratory phase was carried out within the laboratories of the Hunedoara Faculty of Engineering, the Polytechnic University of Timişoara and the industrial research within a steel elaboration and casting plant.

The doctoral thesis was composed under the guidance of Mrs.Prof.Phd.Eng.habil. Socalici Ana Virginia, whom I would like to express my gratitude for her support throughout my doctoral studies. I thank the guidance committee, Mrs.Conf.Phd.Eng. Ardelean Erika and Conf.Phd. Bistrian Diana, and to the Director of Department Ș.l.Phd.Eng. Puțan Vasile for the guidance and help provided during the experiments performed, the processing of the obtained data and the finalization of the doctoral thesis. The suggestions and discussions with the members of the respective guidance commission with members of the engineering and management department, led to the permanent improvement of the thesis as well as the elaboration of scientific articles

I also thank Mr. Prof.Phd.Eng. Heputţ Teodor for the support and advice provided, and for sharing the didactic and professional knowledge. I thank the teachers and researchers from the Research Institute for Renewable Energy Timișoara and the Faculty of Materials Science and Engineering at the Polytechnic University of Bucharest for their support in characterizing the tests experimental. Also, I would like to express my gratitude Phd.Eng. Ioan Romulus Director of the TMK Plant Resita for the support provided in conducting the industrial experimental research within the doctoral thesis. Last but not least, I would like to thank the management of the Polytechnic University of Timișoara, the Hunedoara Faculty of Engineering and the Department of Engineering and Management, for ensuring the favorable framework throughout the elaboration of the doctoral thesis.

CHAPTER 1

EXPERIMENTATION
AND RESEARCHES PLAN

In addition to the main manufacturing product, the steel and waste products, small waste and powdered iron and carbon content, alloying elements, result in a number of by-products and waste, small waste and powders, iron and carbon, as well as oxides, continuously in appreciable quantities, proportional to the production achieved. Quantities generated on current manufacturing flows are added to existing, stored waste quantities and have a negative impact on the environment.

The steel industry is an important sector of the economy where the concept of sustainable development is operationalized and the circular economy must be implemented by recycling by-products and training them in by-products used in the steel or other industries sectors of activity as components of natural capital (raw materials, auxiliary materials, etc).

Further research is needed to establish the best performing processes or recycling technologies from a technological, economic and ecological point of view.

Research must be oriented towards experiments that determine the qualitative characteristics of small and powdered waste with real recycling potential and the improvement of recycling and recovery technologies, techniques and methods at minimal cost.

The steel industry results in powdered and small ferrous waste, with a high Fe content, chemically bound, sometimes metallic that can replace the raw material, respectively iron / cast iron ore/scrap in steel production processes.

The fundamental objective of this doctoral thesis is to identify solutions for processing and capitalizing on small and powdered waste with iron content resulting from the process of elaboration and processing of steel.The following **specific objectives** have been set to meet the fundamental objective:

- Analysis on the situation of small and powdered wastes containing iron resulting from the process of elaboration and processing of steel;
- Analysis of the current state of technologies and processes for capitalizing on small and powdered ferrous waste;
- Qualitative and technological characterization of small and powdered wastes with iron content resulting from the process of elaboration and processing of steel;
- Carrying out laboratory phase experiments on the possibilities of processing and capitalizing on small and powdered wastes containing iron resulting from the process of elaboration and processing of steel;
- Stailing the optimal recipes for processing small and powdered waste with iron content resulting from the process of elaboration and processing of steel;
- Industrial verification of the data of the results obtained during the laboratory phase experiments;
- Global analysis of results;
- Formulation of original conclusions and contributions as well as identification of future research directions on the topic addressed.

The doctoral thesis **Valorification of small waste resulting from the process of elaboration and processing of steel** is structured in two parts, seven chapters followed by final conclusions, original contributions, dissemination of research results, bibliography and annexes.

The 1st part - Current state of the research on the valorification of small and powdered waste from the steel industry contains two chapters examining the current state of steel development technologies with the highlighting of the generation of small and powdered waste containing iron, characterization of these by-products and identification of techniques, technologies and methods for their transformation into by-products usable in the steel industry as components of natural capital by expanding the raw materials base.

Chapter 2 – Small iron-containing waste and powders from the steel industry have sources of powdered and small iron-containing waste, the main technological characteristics, as well as the stage of their valorification at national and international level.

Chapter 3 - The analysis of waste recovery technologies resulting from the steel industry presents the global situation of methods, processes and technologies for processing small and powdered waste containing iron.

The 2nd part – Our own research and experiments on the recovery of waste resulting from the process of steel development and processing, is structured on four chapters and presents our own research carried out in the laboratory phase on the identification of solutions for processing and recovery of powdered and small waste in the steel industry.

Chapter 4 - Qualitative characteristics of small and powdered ferrous waste resulting from the steel industry show the qualitative and technological characterization of waste samples, performed in the laboratories of the Hunedoara Faculty of Engineering respectively of the Institute of Renewable Energy Research within the Polytechnic University of Timișoara. The samples subject to the determinations were taken from the companies ArcelorMittal Hunedoara, TMK Resita, SC Hoeganaes Corporation Europe SA Buzău and various companies that process or have small and powdered landfills. A number of characteristics of by-products resulting from the steel industry have been determined, namely: chemical analysis, granulometric, natural slope angle, bulk density, kinetics of wetting materials and their mineralogical and morphological analysis.

Chapter 5 - Laboratory phase experiments on the valorification of small and powdered waste containing iron present the results and the by-products obtained from experimental laboratory research conducted at the Hunedoara Faculty of Engineering. Laboratory tests were performed on existing equipment and pilot installations in the respective Metal Melts laboratory in the Faculty's Technological Hall. Possibilities for the recovery of small and powdered ferrous waste have been experienced and identified, using classical technolgies (briquetting, agglomeration, pelletizing) with experimental by-products (briquettes / agglomerate/pellets) usable as raw material in the steel industry.

Several batches of recipes have been experienced for each processing technology. Waste from the steel industry, small waste and powdered iron-containing wastes, including: ferrous sludge, scalestorming, were used for experimental laboratory tests, agglomeration-furnal sludge, scale, ferrous slag, sider waste concentrate, steel powder. Approximately 8 batches of recipes of 10-12 recipes for briquetting processing, 6 recipes for agglomeration processing and 10 recipes for pelletizing processing were tested. The by-products obtained were characterized qualitatively and technologically and for each batch of by-products (briquettes/ agglomerate / pellets) the degree of iron recovery was determined, by using them in the metal load of the induction furnace in the laboratory.

Chapter 6 - Optimizing the structure of experimental recipes in waste processing in the form of briquettes presents the mathematical modeling of experimental data performed, by applying the method of designing experiments, the small squares method and genetic algorithms. To establish correlation relationships between technological factors for compressive resistance of experimental briquettes, the data was processed in the Matlab calculation program, the optimization being done using genetic algorithms. Using the response surface method, the connection between the process parameters and its characteristic responses as surfaces in the multidimensional space of the variables was determined. Independent variables were varied simultaneously, taking a limited number of values in the field of experimentation considered. The obtained results lead to the improvement of the performance of the studied process and a technological analysis of the correlations presented allowed the identification of the optimal variation intervals for the composition of the recipes of the experimental by-products.

Chapter 7 – Industrial verification of data on the valorification of small and powdered waste in the form of briquettes presents industrial experiments carried out in a steel plant performed to verify and validate the experimental results obtained in the phase laboratory on the processing of ferrous sludge in the form of briquettes.

Chapter 8 – Final conclusions. Original contributions. Future research directions present final conclusions obtained, original contributions, how to implement in practice the results of research and the directions for further research.

The final part presents the bibliographic sources, the dissemination of research results and annexes.

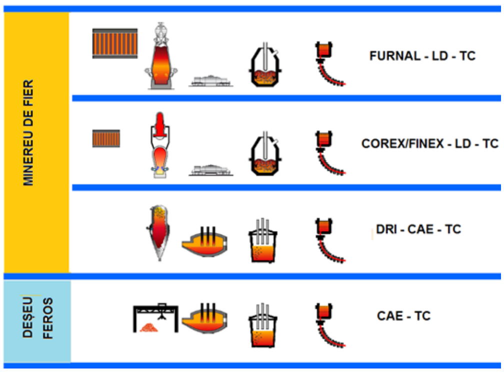
THE 1ST PART
CURRENT STATE OF THE RESEARCH ON THE VALORIFICATION OF SMALL AND POWDERED WASTE FROM THE STEEL INDUSTRY

CHAPTER 2

SMALL IRON-CONTAINING WASTE AND POWDERS FROM THE STEEL INDUSTRY

Steel is a omnipresent material in our lives, this being a durable and recyclable material 100%. Currently, there are four alternative ways to produce steel shown in Figure 1 / 2.13. The first three are based on iron ore as a raw material and the fourth uses ferrous waste in cargo.

Figure 1. Steel-making alternatives [1/22]



In addition to the main manufacturing product, there result by-products and waste, small and large waste, small and large waste containing carbon, iron, alloying elements and sometimes useful components for forming and correcting the chemical composition of slag, carbon dust.

The reported waste is: carbon dust; dust and agglomeration sludge; dust and blast furnace; steel dust (Siemens Martin); electrofilter dust from electric steelworks; dust and converter sludge; scale and scalestorm; iron filings from the polishing of laminates; sham from heat treatments, thermochemicals and anticorrosive coatings; the ferrous fraction of the steel slag.

Efforts are constantly being made to identify and implement the most efficient methods for retaining all possible sources with iron content within the production-use-recycling cycle in order to protect natural resources, reducing the costs and impact of waste disposed of on the environment [2 / 5.3 / 20].

Technologies need to be promoted to ensure [4 / 21-6 / 23]:
- rigorous waste management;
- controlled storage of all categories of waste;
- reduction at source of the quantity and harmfulness of the waste produced.

The steel industry is one of the energy consuming industries in the world, the steel manufacturing process requiring a large amount of energy, which can be saved by reintroducing ferrous waste into the alloying and casting sector, which also generates annual CO2 emissions savings. Figure 2 / 2.30 shows examples of applications of by-products in the steel industry [7/33].

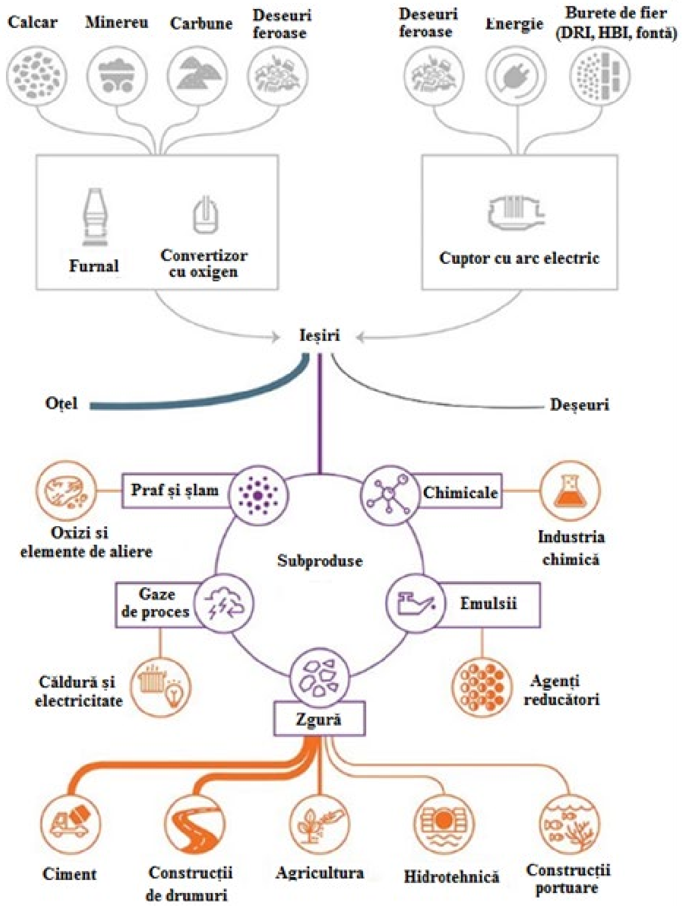


Figure 2. Applications of by-products in the steel industry [7/33]

- The strategy for the development of the metallurgical industry, worldwide, consists in the development of high-performance technologies in order to reduce emissions and increase the recovery and recycling of by-products [32.33].
- From the analysis of the qualitative characteristics (chemical and particle size composition) of the waste, its genesis and the existing quantities (deposition, respectively current results on technological flows), the following can be concluded:
- powdered and small ferrous waste results from the steel industry but also from other industries;
- in the West and North - West (Hunedoara, Călan, Red Steel and Resita) there are large amounts of ferrous waste (a large part stored and a part resulting from technological processes on steel manufacturing flows);
- -the analyzed waste, resulting from the steel industry, has a different iron content and varies within 20 – 87%;
- -in addition to iron, some of the waste from the steel industry also has a high carbon

content of 14 – 36% as well as basic components (CaO and MgO) or fluidifier (Al2O3), which have a role, in the recycling process, as binders or fluidifiers, in addition to recovering the useful element (iron).

Currently, there is an increase in the share of the use of iron-containing waste (pellets, briquettes, agglomerated) and scrap in the metal load of steel-making aggregates. The use of iron-containing by-products in the development aggregates generates substantial energy reductions. The material efficiency indicator measures the percentage of raw materials used in the steel industry to turn crude steel into products and by-products. The main objective of the steel industry is zero waste, so that the recovery and use of by-products within and outside the steel industry, combined with the responsible management of natural resources, contributes to the efficiency of materials and the prevention of waste generation.

CHAPTER 3

THE ANALYSIS OF WASTE RECOVERY TECHNOLOGIES RESULTING FROM THE STEEL INDUSTRY

Waste processing is a large complex of technological operations, mechanical preparation ( ) and thermal (thermal), for bringing them into a form that allows their rational recovery. The choice of waste preparation technologies is determined by their chemical composition, in the form in which the useful or harmful elements of waste are located and the particularities of their physical properties (especially the granulometric ones).

The complexity of waste properties does not allow their preparation through a single operation. The transformation of waste into by-products or raw materials, for the steel industry or other industries, takes place through a succession of operations and metallurgical processes that are constituted in the processing of technological flows [8/40].

Depending on the properties of the waste and the purpose pursued, the preparation operations are performed by: physico-mechanical methods, without chemical or structural transformations and physico-chemical methods, with chemical and structural transformations. Preparation operations used: granulation modification or improvement operations and concentration (shattering, classification, concentration), transformation into pieces of fine materials (briquetting, pelletizing and agglomeration – sintering), auxiliary operations (water removal by mechanical processes – de-sampling, thickening, filtration or by thermal processes – drying; air or gas dust removal; mixing and homogenization; etc.).

Waste is prepared to remove certain harmful substances or elements (lead or zinc from ferrous materials, scale oils, etc.). Technologies such as hydrocycloning, pelletizing, briquetting, agglomeration perform a correction of the granulometric composition as well as a separation at a high yield of non-ferrous metals from the composition of small ferrous and powdered waste. The analysis of processes and technologies for the recovery of small and powdered waste containing iron resulting from the steel industry shows the following conclusions:

-when choosing the recovery process and technology, both the characteristics of the waste, the quantity of waste available and the result on current technological flows must be taken into account, the possibility of concomitant processing of several wastes and last but not least the destination of the product obtained (steel industry);

- unconventional waste recycling processes allow to obtain a product with a high metallic iron content;

- recovery of waste by the classic processes (agglomeration, briquetting and pelletizing), can provide by-products usable in the steel industry as a raw material for the elaboration of steels;

- in the research and experiments of the present paper there will be applied the technologies for capitalizing on the powder waste by briquetting / agglomeration / pelletizing;

- recovery of waste by briquetting / agglomeration / pelletizing, is of particular interest for heavily restructured steel units and large quantities of waste stored on dumps and ponds, in addition to those resulting from current flows.

The resulting by-products can be used in the steel industry as a raw material in quantities of 15-25%. Account must also be taken of the problems faced by factories in terms of the quality of scrap metal, which in many cases introduce unwanted elements into steel into the metal load of aggregates.

THE 2nd PART – OUR OWN RESEARCH AND EXPERIMENTS ON THE RECOVERY OF WASTE RESULTING FROM THE PROCESS OF STEEL DEVELOPMENT AND PROCESSING

CHAPTER 4

QUALITATIVE CHARACTERISTICS OF SMALL AND POWDERED FERROUS WASTE RESULTING FROM THE STEEL INDUSTRY

Iron waste from the steel industry is: agglomeration dust and sludge, blast furnace dust and sludge, converter dust and sludge, steel dust, slag, scale and the scale sludge.

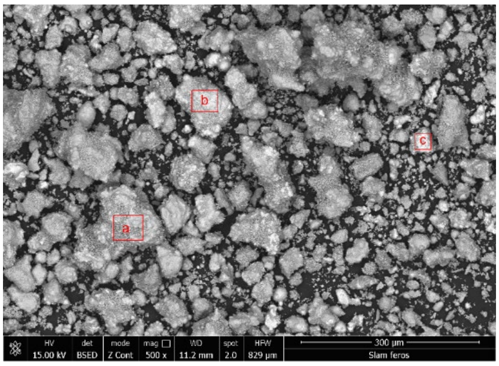
Samples of small and powdered ferrous waste resulting from current technological flows of cast iron and steel production as well as waste already stored have been taken to carry out the experiments and to obtain the by-products of the thesis, namely: Agglomeration-furnal; Furnace powder; Converter sludge; Converter powder; Steel powder; Steel slag; Scale; Scale sludge; Ferrous shawl.

The qualitative characterization of the waste samples was performed in the laboratories of the Hunedoara Faculty of Engineering and of the Institute of Renewable Energy Research within the Timișoara Polytechnic University. Also, part of the determinations were made based on collaborations with the Faculty of Materials Science and Engineering from the Polytechnic University of Bucharest. The samples taken were obtained from the companies of ArcelorMittal Hunedoara, TMK Resita and various companies that process or manage landfills for small and powdered ferrous waste.

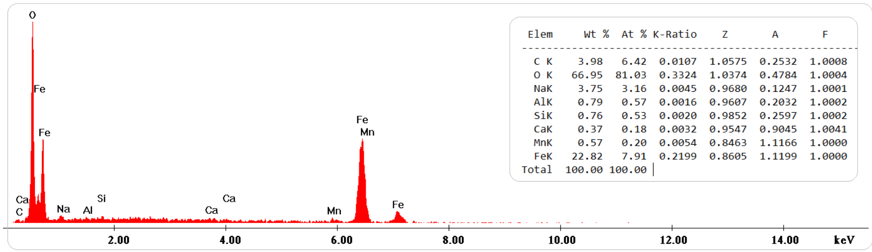
The samples taken were subjected to qualitative analysis, in order to determine the characteristics of the waste, namely:

- Chemical analyzes – were performed by various methods: wet chemistry, electronic scanning microscopy, X-ray distribution and atomic absorption;
- Granulometry of ultrafine materials used DSL method – light diffraction at sedimentation in aqueous medium;
- In the case of materials with a granulation within the limits of 25µm-1mm, the classification was performed with the help of the FRITSCH ANALYSETTE 22 classification installation, and for materials with a granulation greater than 1 mm, the vibrating cyanide (1mm-60mm site set was used, round or square mesh) site;
- The determination of the natural slope angle of the ferrous waste was determined by the method of measurement in the rotating drum;
- Bulk density of materials;
- kinetics for wetting materials;
- Mineralogical and morphological analysis was performed using the electronic microscope with HITACHI model S-2600N scanning equipped with energy-dispersive X-ray spectrometer (EDAX) [9 / 47-11 / 49].

Morphological analysis and qualitative chemical microanalysis of the sample areas are presented in figures 3 / 4.23-6 / 4.26.

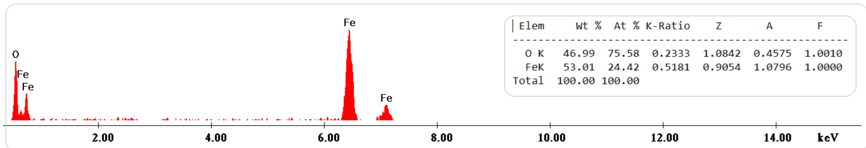


P1, 500x



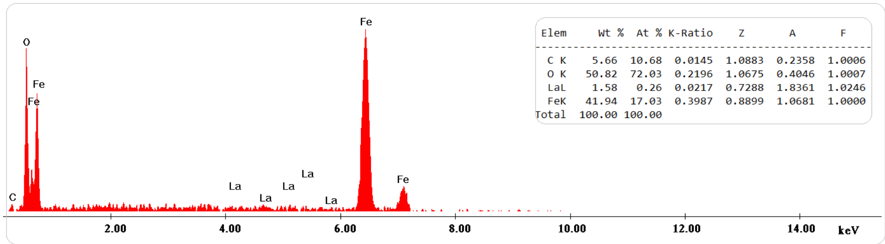
Elem	Wt %	At %	K-Ratio	Z	A	F
C K	3.98	6.42	0.0107	1.0575	0.2532	1.0008
O K	66.95	81.03	0.3324	1.0374	0.4784	1.0004
NaK	3.75	3.16	0.0045	0.9680	0.1247	1.0001
AlK	0.79	0.57	0.0016	0.9607	0.2032	1.0002
SiK	0.76	0.53	0.0020	0.9852	0.2597	1.0002
CaK	0.37	0.18	0.0032	0.9547	0.9045	1.0041
MnK	0.57	0.20	0.0054	0.8463	1.1166	1.0000
FeK	22.82	7.91	0.2199	0.8605	1.1199	1.0000
Total	100.00	100.00				

P1 – a



Elem	Wt %	At %	K-Ratio	Z	A	F
O K	46.99	75.58	0.2333	1.0842	0.4575	1.0010
FeK	53.01	24.42	0.5181	0.9054	1.0796	1.0000
Total	100.00	100.00				

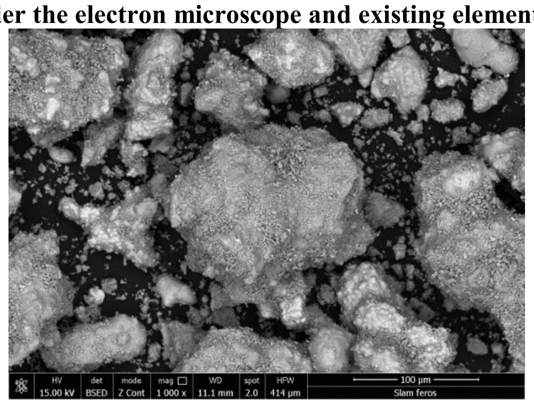
P1 – b



Elem	Wt %	At %	K-Ratio	Z	A	F
C K	5.66	10.68	0.0145	1.0883	0.2358	1.0006
O K	50.82	72.03	0.2196	1.0675	0.4046	1.0007
LaL	1.58	0.26	0.0217	0.7288	1.8361	1.0246
FeK	41.94	17.03	0.3987	0.8899	1.0681	1.0000
Total	100.00	100.00				

P1 – c

Figure 3. Images under the electron microscope and existing elements - P1 ferrous sludge



P2, 1000x

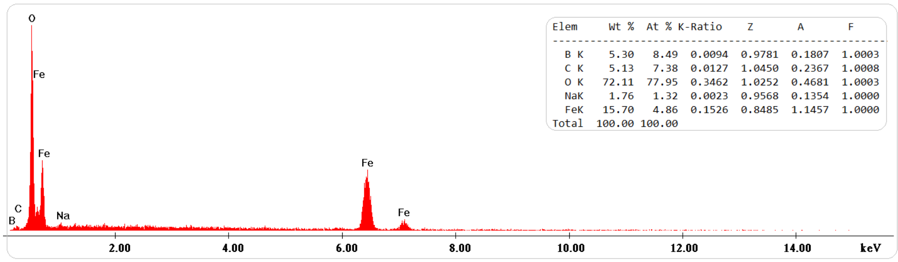
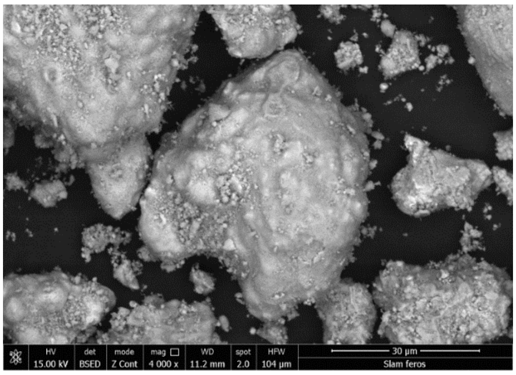


Figure 4. Images under the electron microscope and existing elements – P2 ferrous sludge



P3, 4000x

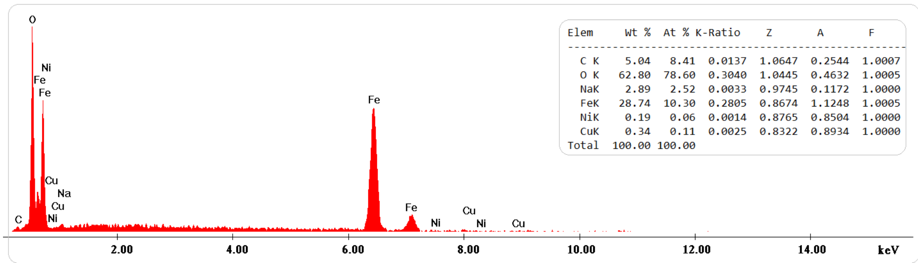
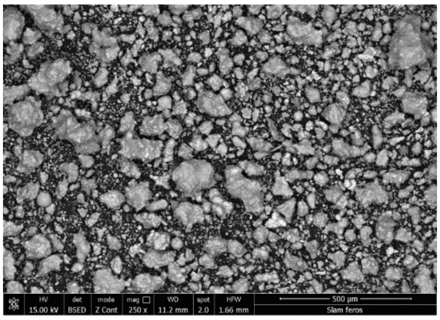


Figura 5. Images under the electron microscope and existing elements – P3 ferrous sludge



P4, 250x

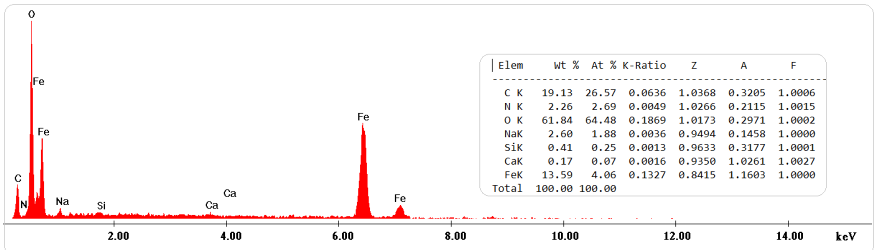


Figura 6. Electron microscope images and existing elements – P4 ferrous sludge

The waste analyzed and characterized from a qualitative point of view, selected for experiments, comes mostly from the Hunedoara industrial area, except for ferrous sludge and steel powder from the production of metal powders - SC Hoeganaes Corporation Europe SA

Buzău and samples of steel dust/converter dust from TMK Resita and Red Steel / Buckets.

The iron content (Fe_{tot}), an average of the samples analyzed, is:

- 81.15% on ferrous sludge;
- 30.40% on the furnace agglomeration sludge;
- 54.35% / 58.12% for coarse / fine converter sludge;
- 71.30% at the scale from ArcelorMittal Hunedoara
- 91.17% for the scale sludge from ArcelorMittal Hunedoara
- 33.12% / at steel slag – ferrous fraction with a grain granulation below 5mm
- 40.70% for steel slag – ferrous fraction with a granulation of 5-10mm
- 49.14% for steel slag – ferrous fraction with a granulation of 10-25mm
- 29.08% for steel powder from ArcelorMittal Hunedoara;
- 43.16% for steelmaking dust from TMK Resita;
- 43.84% on steel powder from Red Steel.

The morphological and compositional characterization of the powdery and small waste containing iron was performed using the electronic microscope with HITACHI model S-2600N scanning equipped with X-ray spectrometer energy dispersive (EDAX). The morphology of all the samples was analyzed, being presented in the images of electron microscopy with scanning - images of secondary electrons and the distribution of X-rays.

The chemical and particle size composition, as well as the content of harmful elements, of the analyzed waste allows their processing by briquetting / agglomeration / pelletizing.

The analysis shows that the waste has a high iron content, and also contains other useful elements in the process of developing ferrous alloys, thus, depending on their qualitative characteristics, the possibilities for recovery result and we can choose the optimal processing technologies from a technological and economic point of view, with ecological implications.

CHAPTER 5

LABORATORY PHASE EXPERIMENTS ON THE VALORIFICATION OF SMALL AND POWDERED WASTE CONTAINING IRON

For the processing of small and powdered ferrous waste containing iron, a series of technological operations are used to transform them into pieces (briquettes, pellets, agglomerated, magnifying glasses, iron sponge).

The technological scheme for processing powdered ferrous waste in order to capitalize on it in the steel industry is shown in Figure 7 / 5.1.

Laboratory experiments performed on the processing of small and powdered ferro-waste waste were performed in the laboratories of the Faculty of Hunedoara Engineering – Polytechnic University of Timișoara.

The following wastes from the steel industry were used for experimental research: ferrous sludge; scale sludge; agglomeration-furnal sludge; Scale; ferrous slag; sider waste concentrate; steel powder.

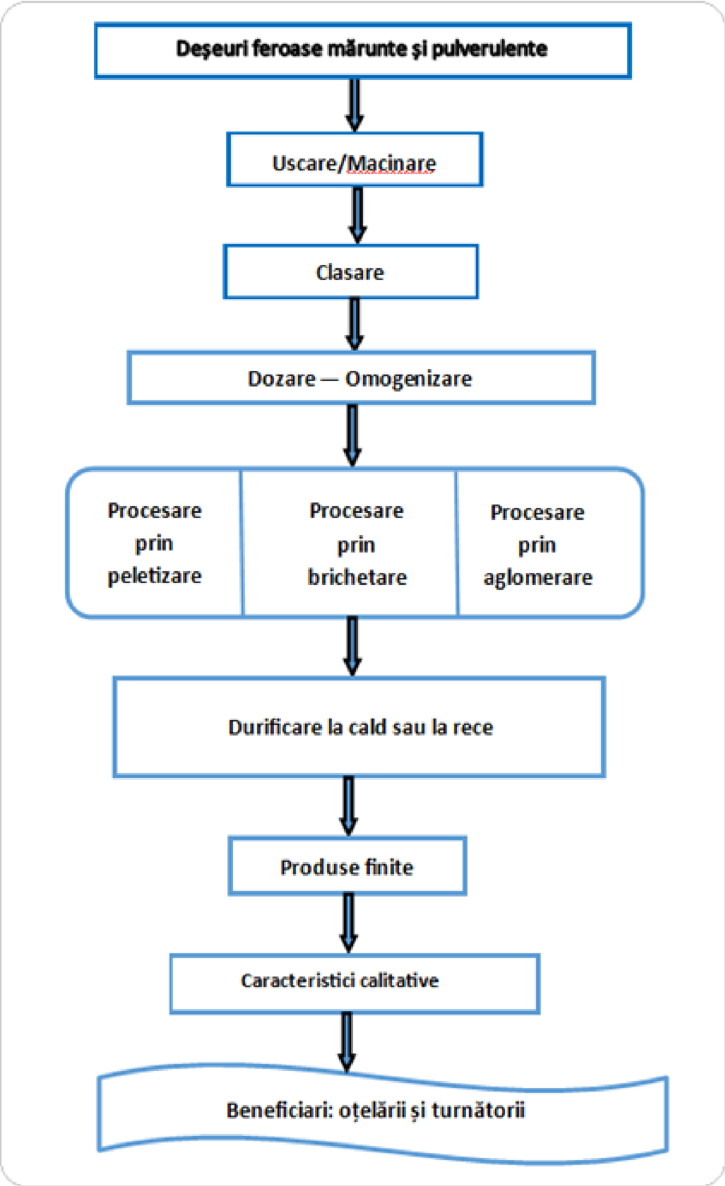


Figure 7. Technological scheme for processing small and powdered ferrous waste

The processing of small and powdered ferrous waste by briquetting is dependent on the choice of waste from the recipes (it must be done by the processor and take into account the available waste), by the demand for resulting products as well as the economic and ecological aspects.

The briquetting process allows the processing of a wide range of waste with an iron content of 30-87% and from a granulometric point of view from microns to a maximum of 10mm. Experimental briquettes are recovered by melting in steel-producing aggregates.

The analysis of experimental data in the laboratory phase, in terms of waste processing by briquetting, shows the following:

- powdered and small ferrous waste resulting from the steel industry, processed by briquetting are: ferrous sludge, scale, scale sludge, agglomeration-furnal sludge, steel slag – ferrous fraction and steel dust;
- the resulting by-products (briquettes) have an iron content of more than 45% and can be used in the load of steel-making aggregates as a raw material in proportion of 5-25%.

In the laboratory phase, a series of briquetting recipes for iron-containing waste were experienced, as follows:

- 10 recipes consisting of – ferrous sludge;
- 4 lots of 12 recipes consisting of – ferrous sludges and trimmer;
- 9 recipes consisting of – ferrous sludges, shear and steel slag;
- 10 recipes consisting of – ferrous sludge, scale sludge and furnace agglomeration sludge;
- 10 recipes consisting of – ferrous sludges and steel powder.

The technological flow of briquetting has been established for each processing variant.

The resulting by-products were subjected to the morphological, structural and topographic characterization respectively, the qualitative and technological characteristics of the experimental briquetteswere determined.

The following by-products were obtained from briquetting processing:

- briquettesof ferrous sludge, not containing added binder and containing added binder (cold and hot), with an iron content of 59-72%;
- briquettesof a tunder with an iron content of 60-65%, consisting of high carbon waste, in addition to iron recovery also contributes to the formation of an active slag respectively to the slag foaming process;
- briquettesof ferrous sludge and steel slag with an iron content of 48-55%;
- ferrous sludge briquettes(ferrous sludge, scale sludge and furnace agglomeration sludge) with an iron content of 60-78.76%;
- ferrous sludge briquettesand steel powder with an iron content of 42-61%.

For experimental briquettes resulting from laboratory tests, the degree of recovery of iron and other accompanying elements in the steel development process was determined. Steel batch was developed in the induction furnace using as raw material 3.5 kg experimental briquettes/ batch. Steel samples were taken to determine the chemical composition of the steel and slag. The additions of briquettesand slag materials were made as they melted. The resulting data were analyzed and an iron balance sheet was calculated for each batch and its degree of recovery from experimental briquetteswas determined.

The following values were obtained for the degree of iron recovery:

- 97.85-98% when using ferrous sludge briquettes;
- 66% when using ferrous sludge briquettes and steel slag;
- 98% when using sludge briquettes(ferrous sludge, scale sludge and blast furnace sludge);
- 68-82% for ferros sludge briquettes and steel powder.

The results obtained in the experiments lead to the conclusion that the analyzed waste can be processed by briquetting (with obtaining for the characteristics of mechanical resistance values higher than the minimum ones for this process), this process allowing the recovery of waste with large limits of variation from a granulometric point of view (desirable below 2mm). The composition of the recipes is established according to the availability of small and powdered waste and the destination of the processed material - steelworks.

For the production of higher qualitative indicators for the products obtained (briquettes), optimizations may be used or a number of other changes to the raw batch recipes may be made, including the use of a binder to eliminate hot hardening – in this case requiring much more rigorous control of the chemical composition, especially in terms of the useful element: iron.

The composition of experimental recipes for the production of the agglomerate in the pilot phase depends on the granulation of materials, the content of Fe_{total} (within the limits of the one existing in ores used in agglomeration) and the carbon content.

The analysis of experimental data in the laboratory phase, related to waste processing by agglomeration, shows the following:

- powdered and small ferrous waste, resulting from the steel industry, processed by agglomeration are: ferrous sludge, scale, scale sludge, agglomeration-furnal sludge, steel slag – ferrous fraction;

- the resulting by-product (agglomerate) has an iron content of more than 42% and can be used in the load of steel-making aggregates as a raw material in a proportion of 5-25% depending on the iron content and the degree of its recovery.

The following by-products were obtained during agglomeration processing:

- agglomerated of ferrous sludge with an iron content of 54-60% and an iron recovery rate of 94%;
- agglomerated of ferrous sludge, shear and steel slag with an iron content of 42-46%;
- agglomerated of sludges (ferrous shlam, scale sludge and furnace agglomeration sludge) with an iron content of 62-65% and an iron recovery rate of 95%.

Regarding products obtained from waste processing with a total iron content between 30% -65% but of a well-known chemical composition it can be considered that they can be considered as a component in the load of electric arc furnaces in proportion of 4-5%, also taking into account the fact that in practice often some of the bark (from slag) have iron content within these limits.

The analysis of the qualitative characteristics (chemical and particle size composition) of the waste used in the experiments shows the following:

- the analyzed waste contained iron different from about 30% in steel slag to about 85% in ferrous sludges;
- in terms of chemical composition and particle size waste can be recovered by recycling, the choice of experimental technology took into account the qualitative characteristics of the waste as well as the destination of the resulting product (briquettes / agglomerate/pellets);
- recovery of waste by classical processes (briquetting / agglomeration / pelletizing) provides by-products (with reduced advanced iron oxides) usable as a ferrous raw material in the steel industry in the steel production sector.

Experimental recipes have been established for each processing technology, as follows:

•Briquette recipes:

- 10 recipes consisting of – ferrous sludge;
- 4 lots of 12 recipes consisting of – ferrous sludges and trimers;
- 9 recipes consisting of – ferro-clamps, Scale and steel slag;
- 10 recipes consisting of – ferrous sludges;
- 10 recipes consisting of – ferrous sludges and steel powder;

•Agglomerated recipes:

- 2 recipes consisting of – ferrous sludge;
- 2 recipes consisting of – ferro-clamps, Scale and steel slag;
- 2 recipes consisting of – ferrous sludges;

•Pellet recipes:

- 10 recipes consisting of – ferrous sludge.

Laboratory phase experiments on the possibilities of recovery of powdered ferrous waste led to the production of **experimental by-products**: **briquettes**, **agglomerates** and **pellets**.

The analysis of the process of processing small and powdered ferrous waste, resulting from the steel industry, for recovery, shows the following conclusions:

- powdered and small ferrous waste, processed by briquetting / agglomeration / pelletizing are: ferrous sludge, scale, scale sludge, agglomeration-furnal sludge, steel slag – ferrous fraction and steel dust;

- resulted **experimental by-products (*briquettes/ agglomerates/ pellets*.)** have an iron content of 42-80% and can be used in the load of steel-making aggregates as a raw material in a proportion of 5-25%;
- - the choice of the respective processing variant of the by-product (briquettes / agglomerate / pellets) result is made according to the available waste varieties, the addition of binders, water and their particle size finesse as well as existing technologies;
- - the reintroduction into the economic circuit of small and powdered waste in the form of briquettes, agglomerated or pellets in various percentages of the ferrous load of steel aggregates have economic but also ecological advantages.

The approach, resolution and implementation of ferrous waste recovery technologies depends on the nature of the materials subjected to processing (powdery and small) and the shape of the finished product (briquettes / agglomerate / pellets), under which these materials are processed. The processing of small and powdered ferrous waste can be done through various processes, the choice must be made by the processor, which must take into account the demand for resulting products, economic and ecological aspects.

CHAPTER 6

OPTIMIZING THE STRUCTURE OF EXPERIMENTAL RECIPES IN WASTE PROCESSING IN THE FORM OF BRIQUETTES

Mathematical modeling of experimental data was performed by applying the method of designing experiments, the least squares method and genetic algorithms.

To establish correlation relationships between technological factors for compressive resistance of experimental briquettes, the data were processed in the Matlab calculation program, the optimization being done using genetic algorithms.

Using the response surface method [12 / 85-14 / 87], the connection between the parameters of this process and its characteristic responses as surfaces in the multidimensional space of the variables is further determined. In experiments conducted according to this method, independent variables are varied simultaneously, taking a limited number of values in the field of experimentation considered, called levels. With the help of this method, although the three independent variables are varied simultaneously, their main and superior effects, as well as the interactions between them can be determined separately. Modification of independent variables will automatically lead to changes in output data. The results thus obtained can be used to improve the performance of the studied process.

Considering the case of a process with three parameters x_1, x_2, which may vary within the limits $x_{1a} \le x_1 \le x_{1b}, x_{2a} \le x_2 \le x_{2b}$ and $x_{3a} \le x_2 \le x_{3b}$, the surface in the plane of independent variables represents the experimental region, and the points of this surface, having different triples of values of the parameters $\left(x_{1i}, x_{2i}, x_{3i}\right)$, represents the experimental points. The surface on which the answers corresponding to each experimental point are located represents the response surface of the considered characteristic of the process.

Second-order models best approximate the called response surfaces and r*egression surfaces*:

$$f\left(x_1, x_2, x_3\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \\ + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \beta_9 x_2 x_3 + \varepsilon \quad (1/6.1)$$

In the matrix notation the relationship (1) becomes

$$[y]=[x]^T[\beta]+[\varepsilon] \qquad (2/6.2)$$

where $[x]$ represents the vector of factors and their contributions to the model

$$[x]^T=\begin{bmatrix}1 & x_1 & x_2 & x_3 & x_1^2 & x_2^2 & x_3^2 & x_1x_2 & x_1x_3 & x_2x_3\end{bmatrix} \qquad (3/6.3)$$

$[y]$ represents the vector of the observations of the response in those experiments, $[\varepsilon]$ represents the vector of measurement errors, and $[\beta]$ is the vector of the coefficients of the regression surface

$$[\beta]=\begin{bmatrix}\beta_0 & \beta_1 & \beta_2 & \beta_3 & \beta_4 & \beta_5 & \beta_6 & \beta_7 & \beta_8 & \beta_9\end{bmatrix} \qquad (4/6.4)$$

to be determined

To determine the coefficients of the response surface using experimental data, the most suitable is the least squares method [12 / 85.14 / 87-16 / 89], which ensures a minimum dispersion of the determined coefficients. For this purpose, the objective function of form is considered

$$F(\beta_0,\beta_1,...,\beta_9)=\sum_{i=1}^{N}\left(y_i-f(x_1,x_2,x_3)\right)^2 \qquad (5/6.5)$$

It follows that the determination of the coefficients of the response surface is equivalent to the following problem of minimizing the objective function.:

$$\min_{\beta} F(\beta_0,\beta_1,...,\beta_9)=\sum_{i=1}^{N}\left(y_i-f(x_1,x_2,x_3)\right)^2 \qquad (6/6.6)$$

which leads to a system of algebraic equations of the type:

$$\frac{\partial F(\beta_0,\beta_1,...,\beta_9)}{\partial\beta_0}=0,...,\frac{\partial F(\beta_0,\beta_1,...,\beta_9)}{\partial\beta_9}=0 \qquad (7/6.7)$$

Basically, the coefficients of the radius surface that shape the process in the study are given by the expression:

$$[\beta]=\left([X]^T[X]\right)^{-1}[X]^T[Y] \qquad (8/6.8)$$

To validate the regression model it is necessary to calculate the correlation coefficient R^2, which measures „ the approach ” of the response surface by the experimental points and has the expression

$$R^2=\frac{SS_R}{SS_T} \qquad (9/6.9)$$

$$SS_R=\sum_{i=1}^{N}\left(f(x_1,x_2,x_3)-y_i\right)^2,\ SS_T=\sum_{i=1}^{N}\left(f(x_1,x_2,x_3)-\bar{y}\right)^2,\ \bar{y}=\frac{1}{N}\sum_{i=1}^{N}y_i \qquad (10/6.10)$$

where SS_R represents the sum of the squares of the errors compared to the experimental observations, and the SST measures the total variation of the N observations.

The problem of determining the optimal parameters that maximize the response surface was solved using genetic algorithms [17/90-20/93]:

$$\max_{(x_1,x_2,x_3)^{optim}} f(x_1,x_2,x_3) \qquad (11/6.11)$$

For example: - for establishing correlation relations between technological factors of compressive resistance of experimental briquettes obtained from ferrous sludges (ferrous sludgem, scale sludge and blast furnace sludgem), the data were processed in the Matlab calculation program, the optimization being done using genetic algorithms.

In the optimization performed, the following notations were performed:
x_1 – ferrous sludge, %
x_2 – Scale sludge, %
x_3 – Sludge agglomeration furnaces, %
y_1 – R_f – crack resistance, N/mm^2
y_2 – R_s – crush resistance, N/mm^2
y_3 – $I_s=R_s-R_f$ - Crush interval, N/mm^2

Applying the method of design of experiments (Design Of Experiments) [15/88-17/90], the table of necessary experiments was generated, carried out in the case of three parameters (factors), where the factors take the extreme and central values in their ranges of variation (table 1 /6.5). Such a set of experiments is called a central or Box-Behnken experimental design [15/88-17/90].

The response surface that models the cracking resistance y_1 as a function of the parameters x_1 – ferrous sludge, x_2 – Scale sludge, x_3 – the sludge agglomeration furnaces, has the expression

$$y_1(x_1,x_2,x_3) = 4.00 + 0.0219x_1 + 0.0393x_2 - 0.025x_3 + 0.000156x_1^2 - \\ - 0.000612x_2^2 - 0.0200x_3^2 + 0.00125x_1x_3 + 0.00429x_2x_3 \quad (12/6.15)$$

having a correlation coefficient $R^2 = 88.62\%$.

Table 1.
Table of experiments for the utilization of ferrous sludges in the form of briquettes

Nr. recipe	x_1	x_2	x_3	y_1	y_2	y_3
1	100	0	0	7	14	7
2	95	2	3	5	8	3
3	90	5	5	4	6	2
4	80	10	10	5	10	5
5	70	20	10	6	12	6
6	60	30	10	4	8	4
7	50	40	10	4	7	3
8	40	50	10	6	10	4
9	30	60	10	7	12	5
10	20	70	10	5	8	3

The results of the optimization problem (11 / 6.11) are presented in table 2 / 6.6. The response area (12 / 6.15) and related contour lines are shown in Figure 8 / 6.4 for the mean value of the x_1 parameter.

Table 2. Results of the optimization problem for y1

Optimal parameters $(x_1,x_2,x_3)^{optim}$	Maximum value y_1^{max}
(100.0000, 65.4843, 9.5232)	9.5130

The response surface that models the crushing resistance y_2 as a function of the parameters x_1 – Ferrous sludge, x_2 – Scale sludge, x_3 – Sludge agglomeration furnaces, has the expression:

$$y_2(x_1,x_2,x_3) = 10.00 + 0.0563x_1 - 0.0119x_2 + 0.117x_3 - 0.000104x_1^2 - 0.000340x_2^2 - \\ - 0.0567x_3^2 + 0.000179x_1x_2 + 0.00375x_1x_3 + 0.00857x_2x_3 \quad (13/6.16)$$

having a correlation coefficient $R^2 = 88.50\%$.

The results of the optimization problem (11/6.11) are presented in table 3/6.7. The response surface (13/6.16) and the related contour lines are shown in figure 9/6.5 for the average value of the $x_2$parameter.

Table 3. Results of the optimization problem for y_2

Optimal parameters $(x_1,x_2,x_3)^{optim}$	Maximum value y_2^{max}
(100.0000, 70.000, 9.6293)	18.6088

The response surface that models the crushing interval y_3 as a function of the x_1 parameters– Ferrous sludge, x_2 – Scale sludge, x_3 – Sludge agglomeration furnaces, has the expression:

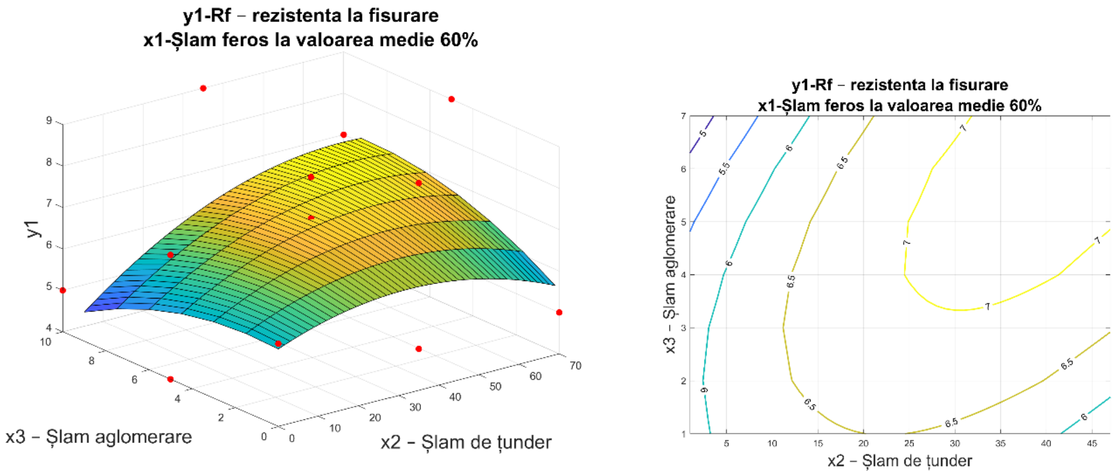
$$y_3(x_1,x_2,x_3) = 5.03 + 0.0531x_1 - 0.0298x_2 + 0.092x_3 - 0.000339x_1^2 + 0.000170x_2^2 - 0.0317x_3^2 + 0.00250x_1x_3 + 0.00429x_2x_3 \quad (14/6.17)$$

having a correlation coefficient $R^2 = 76.51\%$.

The results of the optimization problem (11/6.11) are presented in table 4/6.8. The response surface (14/6.17) and the contour lines are shown in figure 10/6.6 for the average value of the parameter x_3.

Table 4. Results of the optimization problem for y_3

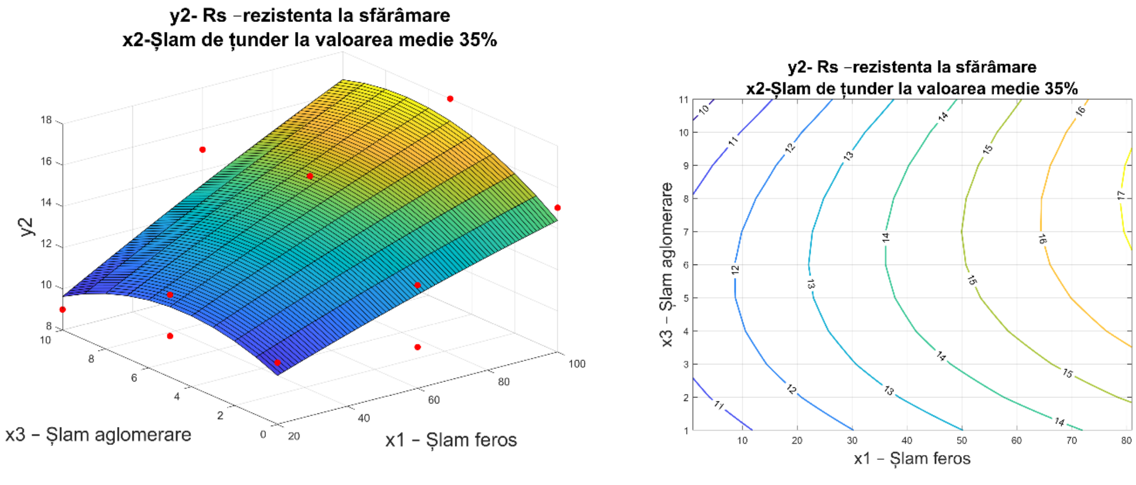
Optimal parameters $(x_1,x_2,x_3)^{optim}$	Maximum value y_3^{max}
(100.0000, 70.000 , 10.000)	8.9500



Suprafața de regresie $y_1 = f(x_{1med}, x_2, x_3)$ Curbele de nivel

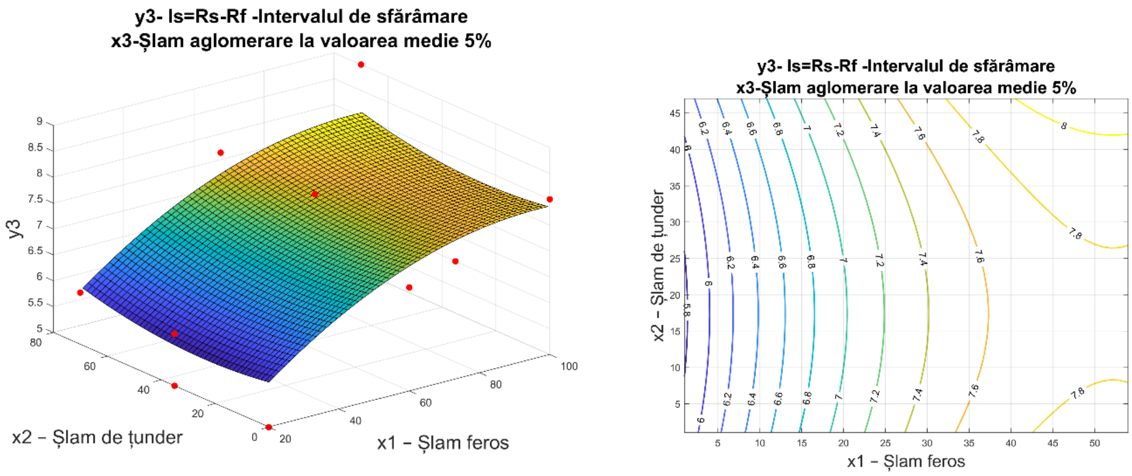
Figure 8. $y_1 = f(x_{1med}, x_2, x_3)$

From the analysis of the presented correlations (regression surfaces and level curves) it is found that for values of the scale sludge in the range of 15-50%, values of the agglomeration sludge in the range of 5-10% respectively for values of the ferrous sludge 40-100 % very good values are obtained for the crack resistance Rf ≥ 6.5N/mm2. The best results (in terms of chemical composition and compressive strength) are obtained for briquettes containing ferrous sludge (90-100%). Depending on the available raw material (slurries), comparable results can be obtained by replacing the ferrous sludge with the pruning sludge in the recipes up to a maximum of 50% and a maximum of 10% furnace agglomeration sludge.



Regression surface $y_2 = f(x_1, x_{2\ med}, x_3)$ Level curves

Figura 9. $\mathbf{y_2 = f(x_1, x_{2med}, x_3)}$



Regression surface $y_3 = f(x_1, x_2, x_{3\ med})$ Level curves

Figura 10. $\mathbf{y_3 = f(x_1, x_2, x_{3med})}$

Depending on the availability of waste (raw material for the production of briquettes), the following is recommended:

- Production of briquettes from 100% ferrous sludge;
- Production of briquettes which, in addition to ferrous sludge, contain one or two wastes (slag, slag, steel mill slag – ferrous fraction, furnace agglomeration sludge, steel mill dust), as follows: steel mill slag 15-25%, slag 20-40%, 15-50% tunder sludge, furnace agglomeration sludge 5-45% respectively LF slag 5-10%;
- Experimental briquettes are used as a raw material for steelmaking in electric arc furnaces, in the proportion of 5-25% of the load, depending on the quality of the steel developed;
- The resulting by-products – the experimental briquettes are used in the steel industry.

CHAPTER 7

INDUSTRIAL VERIFICATION OF DATA ON THE VALORIFICATION OF SMALL AND POWDERED WASTE IN THE FORM OF BRIQUETTES

Starting from the results obtained during the experiments in the laboratory phase, the industrial verification of the data regarding the valorization of pulverulent ferrous waste (ferrous sludge) in the form of briquettes in the steel industry is presented below. The briquettes (E3P assortment) are processed from pulverulent and small ferrous waste (ferrous sludge) at a waste processing company in the Hunedoara Industrial Park and shipped to the beneficiaries - steel plants.

Figure 11/7.8 shows the metal load of the prepared steel batches highlighting the E3P assortment – ferrous slurry briquettes, this assortment being used in a quantity of approximately 20 t/batch (19.75t/batch–25.10t/batch) respectively 15 ,7-20.05% - on average 16.8%.

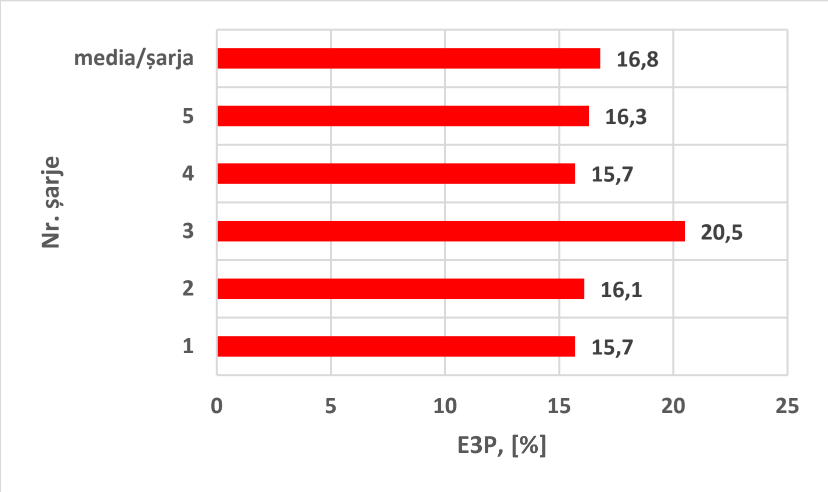


Figure 11. The E3P range used in the metal charge of steel batch

The analysis of experimental data shows the following:

- The copper content at melting, the copper content at the end of the elaboration and the final copper content fall within the product standard for continuously cast semi-finished products obtained during the experiments;
- The copper content in the sample taken at melting is about 0.01 – 0.05% higher than at the end of the steel treatment;
- To obtain the copper content, according to the standard required by the beneficiary, within the limits of 0.2-0.22%With the amount of ferrous waste with low copper content E2 and E6 respectively must vary within 40 - 46 t / batch limits, having regard to the E1 assortment having a copper content of 0,30-0,35%;
- The use of E3P assortment does not lead to an increase in copper content in the elaborate steel;
- As regards the molybdenum content, it is melting on average 0.05%, it follows that the E3P assortment has led to an increase in molybdenum content of 0.02%Mo (equivalent to 35 kg FeMo / batch), so part of the ferro-alloys used can be replaced;
- The use in the load of the electric arc furnace of the E3P assortment, on average 16% / batch, leads to a saving of raw materials (can replace the deficient scrap metal assortments, without influencing the quality of the steel developed);
- No exceedances of energy, fuel, oxygen consumption were found in the cargo use of the E3P compartment, falling within the technological regulations in force.Obținerea oțelului presupune materii prime, investiții, energie și forță de muncă.

Currently, steel is preferred in integrated plants (primary flow / modern-otel technologies equipped with oxygen converters, about 70% of the world production of steel) but there are also a number of technical constraints, economic and environmental and in recent years there has been an increase in the share of steel developed in mini-zines (modern technologies and steel molds equipped with electric furnaces with arc-continuous secondary-casting treatment installations, about 30% of world steel production).

The main problems encountered by the steel industry:

- the quality of the raw materials used (exhausted raw materials, very limited or geographically not inaccessible supply, limited flexibility in terms of production, use of very complex complementary gas treatment systems, etc);
- large capital investments (high operating costs, small margins, low machine efficiency, etc)
- environmental problems (obtaining the authorization for construction and operation very difficult; by-products difficult to capitalize; a large amount of wastewater, carbon footprint, etc.)

Thus, in the case of the recovery of ferrous waste, in the context of the circular economy, by using the by-products obtained as a raw material, a series of advantages are obtained: economic and ecological technologies.

The expansion of the raw material base in the steel industry by the reintroduction into the economic circuit of small and powdered ferrous waste leads to savings in raw materials, material, energy and fuel. By-products obtained and used as quality raw materials are also superior to part of the scrap metal categories used in steel development aggregates.

CHAPTER 8

FINAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS. FUTURE RESEARCH DIRECTIONS

Analyzing the literature and the results of ourown experimental research, on the recovery of powdered and small iron-containing waste resulting from the steel industry, the following final conclusions result:

- waste from the steel industry contains metal iron or chemically bound iron, its content varies within 20-75%;
- in addition to iron, some of the waste from the steel industry also have a high carbon content of 14 – 36% as well as basic components (CaO and MgO) or fluidifier (Al_2O_3), which can be used, in the recycling process, as binders or fluidifiers, in addition to recovering the useful element (the) iron;
- there is currently an increase in the share of the use of iron-containing waste in the form of by-products (pellets, briquettes, agglomerated) in the metal load of steel-making aggregates;
- the use of iron-containing by-products in the development aggregates generates substantial reductions in raw materials, fuels and energy;
- recovery of waste by classical processes (agglomeration, briquetting and pelletizing), can provide by-products usable in the steel industry as a raw material for the production of steels;
- in the research and experiments performed, the technologies for recovery of powdered waste by briquetting / agglomeration / pelletizing were applied;

- recovery of waste by briquetting / agglomeration / pelletizing, is of particular interest for heavily restructured steel units and large quantities of waste stored on dumps and ponds, in addition to those resulting from current flows;

- in laboratory research and experiments, the following small ferrous and powdered wastes were analyzed - ferrous sludge, agglomeration-furnal sludge / blast furnace powder, converter dust/converter sludge, steel powder, ferrous fraction of steel slag, scale / sludge and sider waste - waste frequently resulting from current technological flows, as well as those stored as a result of disused technological flows of steel processing;

- the morphological and compositional characterization of the powder and small waste containing iron was carried out using the electronic microscope with HITACHI model S-2600N scanning equipped with dispersive X-ray spectrometer in energy (EDAX);

- the morphology of all the samples was analyzed, being presented in the images of electron microscopy with scanning - images of secondary electrons and the distribution of X-rays;

--the chemical and particle size composition as well as the harmful content of the analyzed waste led to the determination of the variant of their processing by briquetting / agglomeration / pelletizing obtaining the following by-products – briquettes, crowded and pellets.

The analysis of experimental data in the laboratory phase, regarding the **processing of waste by briquetting**, results in the following:

- powdered and small ferrous waste resulting from the steel industry, processed by briquetting are: ferrous sludge, scale, icing sludge, agglomeration-furnal sludge, steel slag – ferrous fraction and steel dust;

- the resulting by-products have an iron content of more than 45% and can be used in the load of steel-making aggregates as a raw material in proportion of 5-25%.

The following by-products were obtained from briquetting processing:

- ferrous sludge briquettes, not containing added binder and containing added binder (cold and hot), with an iron content of 59-72% and an iron recovery rate of 97.85-98%;
- briquettes of a tunder with an iron content of 60-65%, consisting of high carbon waste, in addition to iron recovery also contributes to the formation of an active slag respectively to the slag foaming process;
- briquettes of ferrous sludge and steel slag with an iron content of 48-55% and an iron recovery rate of 66%;
- (ferrous sludge, 1st sludge and furnace agglomeration sludge) with an iron content of 60-78.76% and an iron recovery rate of 98%;
- ferrous sludge briquettes and steel powder with an iron content of 42-61% and a recovery grade of 68-82%.

The results obtained in the experiments lead to the conclusion that the analyzed waste can be processed by briquetting (with obtaining for the characteristics of mechanical resistance values higher than the minimum ones for this process), this process allowing the recovery of waste with large limits of variation from a granulometric point of view (desirable below 2mm). The composition of the recipes is established according to the availability of small and powdered waste and the destination of the processed material - steelworks. For the production of higher qualitative indicators for the products obtained (briquettes), optimizations may be used or a number of other changes to the raw batch recipes may be made, including the use of a binder to eliminate hot hardening – in this case requiring much more rigorous control of the chemical composition, especially in terms of the useful element: iron.

The analysis of experimental data in the laboratory phase, in terms of **waste processing by agglomeration**, shows the following:

- powdered and small ferrous waste, resulting from the steel industry, processed by agglomeration are: ferrous sludge, scale, scale slam, agglomeration-furnal slam, steel slag – ferrous fraction;

- the resulting by-product (agglomerate) has an iron content of more than 42% and can be used in the load of steel-making aggregates as a raw material in a proportion of 5-25% depending on the iron content and the degree of its recovery.

The following by-products were obtained during agglomeration processing:

- agglomerated of ferrous sludge with an iron content of 54-60% and an iron recovery rate of 94%;

- agglomerated of ferrous sludge, shear and steel slag with an iron content of 42-46%;

- agglomerated of sludge (ferrous slam, 1st sludge and furnace agglomeration sludge) with an iron content of 62-65% and an iron recovery rate of 95%.

Regarding products obtained from waste processing with a total iron content between 30% -65% but of a well-known chemical composition it can be considered that they can be considered as a component in the load of electric arc furnaces in proportion of 4-5%, also given that in practice often some of the bark (from slag) has iron content within these limits.

The analysis of experimental data in the laboratory phase, in the case of **processing waste by pelletizing**, results the following:

- the determination of compressive strength for raw and burnt pellets confirms that such waste can be recovered by pelletizing and the pellets obtained have non-casar resistance for handling and transport to the economic operator for loading into steel furnaces;

- pellets produced from powdered waste containing iron / iron and carbon by combustion can be metallized, which allows their use as a component in the load of furnaces for the elaboration of steels;

- when processing the ferrous sludge by pelletizing, pellets with an iron content of 60-67% and a degree of its recovery of 95-96% were obtained%.

The evaluation of the properties and characteristics of the by-products obtained from a morphological, structural and topographic point of view was performed by electron microscopy (elemental chemical analysis by EDS technique and SEM analyzes), topographic analysis (2D map and 3D images obtained for experimental by-products using LEXT OLS4000 3D Confocal Laser Measuring Microscope) and macrostructural analysis (performed with digital stereomicroscope model 520SZM-D).

Technological analysis of the correlations obtained in briquetting processing, the optimal variation intervals for the wastes from the experimental briquette recipes were identified, as follows:

a) For briquettes consisting of scale, steel slag and furnace agglomeration slam: 20-40% scale; 15-25% slag; 30-40% blast furnace;

b) For briquettes made of (ferrous sludge, scale blade and furnace agglomeration sludge): 40-100% ferrous sludge; 15-50% scale blade; 5-10% agglomeration blast furnaces;

c) For briquettes made of ferrous sludge, LF slag and steel powder: 20-70% ferrous sludge; 5-10% slag LF; 5-30% steel powder.

Depending on the available waste (raw material for the production of briquettes) the following is recommended:

- Production of 100% ferrous sludge briquettes%;

- Production of briquettes consisting of one or two ferrous sham wastes (scale, scale slats, steel slag – ferrous fraction, blast furnace sludge, steel powder), thus: steel slag 15-25%, 20-40% scale, 15-50% scale sludge, 5-45% furnace agglomeration slag and 5-10% LF slag respectively%;

- Experimental briquettes are used as a raw material for the elaboration of steel in electric arc furnaces, in proportion of 5-25% of the load, depending on the quality of the developed steel;

- The resulting by-products – briquettes / agglomerate / experimental pellets have as field of use the steel industry.

Industrial verification of results and experimental data obtained in the laboratory phase confirmed their veracity. By-products obtained (briquettes obtained from ferrous sludge) are used in proportion of 15-20% as a raw material in the load of the electric arc furnace on steel products.

Original contributions

Analyzing the results obtained in laboratory and industrial phase experiments, the following original contributions result:

1. Highlighting important aspects in the processes of generating by-products in the elaboration of steel as well as alternatives for processing small and powdered wastes containing iron;

2. Carrying out a technological synthesis regarding the classical methods, processes and technologies, respectively unconventional for recovery by recycling in steel of the powdery and small ferrous waste;

3. Determination of the qualitative characteristics of powdered and small iron-containing waste resulting from the steel industry;

4. Establishment of waste assortments for laboratory research and experimentation, experimental recipes and their processing technology;

5. Establishment of experimental processing technologies, small waste containing iron, by briquetting, agglomeration and pelletizing;

6. Establishing experimental recipes for each processing technology, as follows:

- Briquettes recipes:

- 10 recipes consisting of – ferrous sludge;
- 4 lots of 12 recipes consisting of – ferrous slams and trimmer;
- 9 recipes consisting of – ferrous slams, shear and steel slag;
- 10 recipes consisting of – ferrous sludge, scale slam and furnace agglomeration sludge;
- 10 recipes consisting of – ferrous slams and steel powder;

- Agglomerated recipes:

- 2 recipes consisting of – ferrous sludge;
- 2 recipes consisting of – ferrous slams, Scale and steel slag;
- 2 recipes consisting of – ferrous sludge, scale slam and furnace agglomeration sludge;

- Pellet recipes:

- 10 recipes consisting of – ferrous sludge.

7. Obtaining experimental by-products (briquettes / agglomerate / pellets) using in small iron-containing waste recipes from the steel industry (ferrous sludge, Scale, Scale sludge, agglomeration-furnal sludge, steel slag – ferrous fraction and steel dust).

8. Study of the morphological, structural and topographic characterization of the waste used respectively determining the qualitative and technological characteristics of the by-products obtained (briquettes, agglomerated, pellets);

9. Mathematical modeling of experimental data performed, applying the method of designing experiments, the least squares method and genetic algorithms;

10. Establishing correlation relations between technological factors of resistance at compression of experimental lighters, optimization being done using genetic algorithms, the results obtained leading to improved performance of the experimental process;

11. Determining the optimal composition of recipes for the production of briquettes, based on the mathematical and technological analysis of the correlations obtained between the

resistance characteristics and the components of the experimental recipes. Optimization of technological parameters in order to establish optimal areas of variation for the components of recipes in order to obtain high quality experimental by-products.

12. Determination of the degree of iron recovery (94-96%) from experimental by-products, using them as raw material for the production of steel in the induction furnace in the faculty laboratory;

13. Morphological, topographical and compositional characterization of the experimental by-products obtained respectively analysis and comparison of the results;

14. The results obtained can constitute well-founded scientific support in terms of technological, economic and environmental performance for the use of the resulting by-products, obtained from small iron-containing wastes from the steel industry, usable as raw material for the production of steel in electric arc furnaces;

15. Establishing the optimal composition of prescriptions for waste subject for experimentation and confirming that they can be capitalized by the classic processes (briquetting, agglomeration and pelletizing) and used successfully in industrial practice in steelmaking.

16. The recovery processes identified in the doctoral thesis offer sustainable solutions for the recovery of small and powdered waste containing iron by using the resulting by-products (briquettes / agglomerate/pellets) as natural capital components in the steel development process.

17. The experimental data obtained may be used as a support for the decision to capitalize on iron-containing waste from the steel industry to obtain by-products and expand the base of raw materials and materials intended for steel manufacturing.

18. Identifying the simplest and most cost-effective recycling methods for easy implementation in industrial practice, at low cost, by waste processing companies or economic agents in the steel industry.

The best results were obtained for experimental lighters made from slams, their recipes being used by the waste processing companies from Hunedoara Industrial Park and used in industrial practice at a steel plant (TMK Resita) as a raw material in proportion of 15-20%.

Research follow-up directions

- Development of research on recycling from powdered and small waste metals (manganese, chromium, nickel, cobalt and tungsten) and their reintroduction into the economic circuit in the context of the circular economy;
- Increasing the degree of recovery of ferrous and non-ferrous metallurgical slag and thermal power plant ash stored in dumps;
- Advanced recovery of non-ferrous metals from pyritic ash.

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