POSSIBILITIES OF USING MATERIALS FROM STEEL DUST RECYCLING IN THE PRODUCTION OF ALLOY STEELS

Stanisław MAŁECKI, [1]Krzysztof GARGUL, [2]Marek WARZECHA, [2]Grzegorz STRADOMSKI, [2]Artur HUTNY, [3]Mateusz MADEJ, [3]Michał DOBRZYŃSKI,

[1]AGH - University of Science and Technology, Faculty of Non-Ferrous Metals, Krakow, Poland, EU, stanmal@agh.edu.pl

[2]Czestochowa University of Technology, Faculty of Production Engineering and Materials Technology, Czestochowa, Poland, EU, marek.warzecha@pcz.pl

[3]Przedsiębiorstwo Produkcyjno-Handlowo-Usługowe STILMAR, Częstochowa, Poland, EU, mateusz.madej@stilmar.pl

https://doi.org/10.37904/metal.2022.4461

Abstract

Steels dusts from electrostatic processes, which are currently a problem in the ecological sense, is a rich but problematic carrier of many elements such as Fe, Zn, Mn, Cr. The existing recycling technologies, unfortunately, do not allow for their full recovery. The authors of the work decided to investigate the possibility of reducing the amount of waste to be deposited to the necessary minimum in the process of steel dust recycling.

The paper presents the possibilities of using a metallic alloy, which was one of the products obtained as a result of the processing of steel dust in a resistance-arc furnace. The main objective of the dust processing research was the management and selective recovery. The products of the process were zinc oxide, slag and iron alloy. Iron recovery from dust was determined at the level of 98 %. The resulting iron alloy contained alloying elements such as manganese, chromium, and silicon in amounts enabling it to be used in the steel production process. The material can be used for the production of, for example, cast steel resistant to erosive and tribological wear.

Keywords: Metallurgy, recycling, steel, cast steel.

1. INTRODUCTION

Significant amounts of dust are generated during the production of steel in electric arc furnaces (EAF). On the one hand, due to its chemical composition, dust is considered a hazardous waste. On the other hand, they contain ingredients that can be recovered. Dust accounts for 1 to 2 % of the mass of the charge to be melted [1,2]. The average annual steel production [2,3] is 1600 million Mg, of which 33 % is produced in the electric arc furnace (EAF), thus, the annual production is from 5 to 10 million Mg of EAF dust. Electric Arc Furnace Dust (EAFD) is a multi-component and multi-phase mixture of elements with different chemical composition and grain size. A typical chemical composition of dusts in terms of metal content can be presented as a mixture of: iron compounds (approx. 40-50 %) and zinc (15-25 %) with mineralogical compounds and a low lead content (approx. 5%), other components of EAF dust it, zinc chloride, heavy metal salts and alkali metal chlorides [1,4–7]. The most popular technology for zinc recycling and iron dust from electric arc furnaces is the Waelz process. Dust from electric arc furnaces is placed in a rotary furnace loaded with coke [8-10]. Coke and CO (from partial oxidation of carbon) reduce zinc oxide to metallic zinc [8,11–15]. The resulting slag is crushed with crushing and then used in road construction as a construction material. The Envirodust Process is also known, in which the feed material is granular slag, coke coal, charcoal and other carbon bearing materials that can be used as reducing agents. The main stage of the process takes place in a plasma furnace. The zinc and lead oxides contained in the liquid bath are reduced to their metal vapors at a temperature of 1400 to 1500 °C and thus pass into the gas phase. Slag and iron alloys are tapped from the furnace. Volatile zinc and lead are led from the furnace to a lead condenser where they condense. The product is raw zinc.

Currently, there is no technology for the comprehensive processing of steel dust and the full management of the resulting products. The authors of this study developed an ecological and sustainable comprehensive technology for the processing of zinc-bearing dust [16]. Zinc bearing metallurgical dust is completely processed into products suifig for economic use. The developed technological process is carried out without waste, and the products are zinc oxide, iron alloys and slag aggregate. The combination of the zinc recovery process with the iron-based alloy smelting process in one unit allows for energy-efficient performance of the process after heating the charge to a temperature above 1400 °C, and enables precise control of the iron alloy smelting process by regulating the composition of the waste charged to the resistance arc furnace, such as and controlling the amount of alloying additives added in the melting step in the ladle furnace. The energy optimization of the process also allows for the treatment of waste with a low zinc content and makes the process economically viable.

The paper presents some of the results of the research aimed at determining the possibility of using the iron alloy formed after the processing of steel dust for the production of various types of steel.

2. RESEARCH METHODOLOGY

The research on the processing of steel dust was carried out in two stages. The first stage consisted of preliminary laboratory tests, which allowed to determine the possibility of waste-free processing of the dust. However, the second stage of the research was carried out on a quarter-technical scale before the technology was implemented.

In the first stage, the research material consisted of dust from the steelmaking process from two different mills. They were characterized by an increased zinc content. **Table 1** shows the average chemical composition of the dusts.

Table 1 Average composition of steel dust processed in laboratory conditions, (wt. %)

Sample	C	S	ZnO	CaO	SiO_2	MnO	MgO	PbO	Al_2O_3	Fe
P1	2.71	0.54	47.00	6.00	3.00	2.50	1.00	3.00	1.00	23.00
P2	0.95	0.14	35.00	6.00	4.00	3.00	2.00	2.00	1.00	32.00

The process of removing zinc from dust and remelting them was carried out in a laboratory induction furnace by LEYBOLD. It is a 40 kW furnace, which enables the smelting of samples weighing up to 8 kg. The process took place in an oxidizing atmosphere. The stripped zinc (oxidized to ZnO) was directed along with the process gases to the extraction system, in which samplers in the form of steel plates with dimensions of 20x20 mm were placed, on which the research material was weaned. After the remelting process, there was also a residual material in the form of metal and slag, which was subjected to qualitative and quantitative analysis. Dusts with a reducing agent in the form of coke breeze with a fraction below 0.05 mm were tested. On the basis of previous tests, it was established that the tests will cover the dust with the addition of 5, 10, 15 and 20 wt.%. reducer. Part of the tests were performed on the basis of samples weighing 50 g in a graphite crucible. The basic tests were carried out on samples with a mass of about 900 g, it was found that this is the optimal mass due to the course of the process and laboratory capabilities.

The test samples were placed in a laboratory furnace with an oxidizing atmosphere. In the first phase of the process, heating of the charge took place and after reaching the temperature above 900 °C, intensive evaporation of the components was observed. The process was carried out until the process "fumes" disappeared. On the basis of the observations, it was found that the time of stripping the components from the tested material, for the 900 g (net) sample, is within the time interval of 45 - 50 minutes.

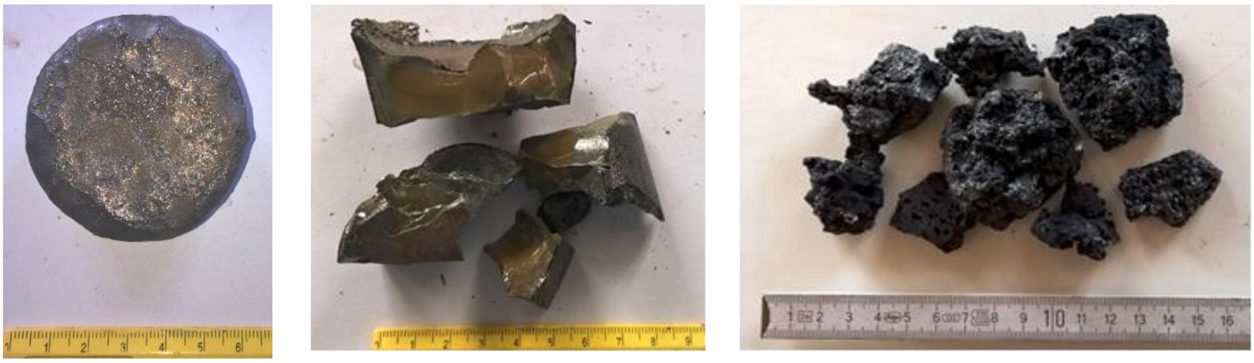
Quarter-technical studies were carried out in an electric resistance arc furnace. **Table 2** shows the average chemical composition of the dusts. Dusts with 15, 17.5, 20 and 25 wt.% Additions were tested. reducer in the form of coal dust. Before the reduction process, the research material was granulated. The reduction of the zinc and most of the iron in the solid state was carried out at a temperature of 1250-1300 °C. The total mass of the processed granulate was 200 kg, while the reduction process lasted 4 hours. After melting the slag, the final iron reduction was carried out for about 2 hours by increasing the temperature of the slag to the temperature of 1450-1550 ° C. As a result of the process, zinc oxide was obtained in the form of dust, iron alloy and slag.

Table 2 Average composition of steel dust processed on a quarter-technical scale, (wt%)

Sample	C	S	ZnO	CaO	SiO_2	MnO	MgO	PbO	Al_2O_3	Fe
P3	2.05	0.45	43.00	4.30	3.90	3.40	2.40	2.20	1.00	38.00

3. RESULTS

As a result of the conducted laboratory experiments, materials were obtained, which were subjected to further research. They were zinc oxide dust, a metallic residue, the so-called residual metal, slag and sinter - residue from the dust processing process, from which it was not possible to isolate the metallic fraction. The view of sample samples of the obtained products is shown in **Figure 1**. The sinter, from which the metallic phase was not separated, was formed during the processing of dusts with the addition of a reducing agent, which was 5 and 10% by weight, respectively. However, after processing the dust samples with a reducer of 15 and 20% by weight, a slag was obtained and the metallic phase.



a) b) c)

Figure 1 View of the products a) metallic part, b) slag, c) "sinter"

The obtained metallic alloy was analyzed by emission spectrometry in order to determine its chemical composition. **Table 3** shows the chemical composition of specific samples of the iron alloy.

Table 3 Average composition of the metallic part obtained from the processing of dusts on a quarter technical scale, (wt%)

Sample	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu
L1	3.32	1.21	0.74	0.44	0.24	0.84	0.03	0.04	0.004	0.40
L2	2.55	1.01	0.21	0.39	0.24	0.92	0.01	0.12	0.003	0.46
L3	4.30	1.90	2.50	0.12	0.06	0.80	0.01	0.50	0.050	0.38
L4	4.28	1.67	0.65	0.06	0.11	0.21	0.02	0.07	0.002	0.46
L5	3.50	0.46	2.63	0.27	0.02	0.52	0.04	0.06	0.005	0.46

As a result of the research carried out on a quarter technical scale, an iron alloy was also obtained, which was cast into flat ingot molds lined with refractory concrete. The average weight of the obtained metal was 53 kg. The view of the obtained iron alloy is shown in **Figure 2**.

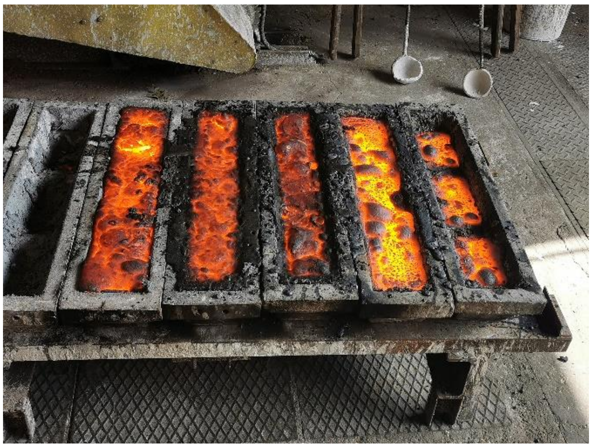


Figure 2 View of the iron alloy cast into ingot molds

Samples were cut from the solidified ingot and analyzed by emission spectrometry. **Table 4** presents the average chemical compositions of the iron alloy obtained on a quarter technical scale.

Table 3 Average composition of the metallic part obtained from the processing of dusts in laboratory conditions, (wt%)

Sample	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu
T 1	5.39	1.61	5.13	0.05	0.24	3.21	0.08	0.03	0.003	0.27
T 2	5.40	0.50	5.21	0.04	0.00	1.21	0.05	0.01	0.073	0.14
T 3	5.40	0.45	6.03	0.04	0.04	1.03	0.07	0.04	0.048	0.35
T 4	4.83	0.44	6.36	0.05	0.01	1.00	0.07	0.05	0.001	0.38
T 5	5.35	0.06	5.60	0.05	0.10	1.17	0.06	0.05	0.000	0.37
T 6	5.40	0.02	5.27	0.06	0.06	1.56	0.06	0.05	0.002	0.26
T 7	4.56	0.04	5.35	0.06	0.03	0.98	0.06	0.05	0.002	0.35
T 8	4.44	0.08	6.18	0.06	0.01	0.87	0.07	0.05	0.000	0.35
T 9	5.32	0.65	7.97	0.07	0.02	0.98	0.09	0.05	0.000	0.35
T 10	5.40	0.09	6.33	0.05	0.01	0.94	0.07	0.05	0.000	0.35

4. DISCUSSION

Chemical compositions of individual metallic phases obtained after reduction of steel dust were analyzed. As a result of the laboratory tests carried out, it was found that the minimum share of the reductant should be 15% by weight. In the case of lower contents, no metallic alloy was obtained. This was due to a reducer shortage. In tests carried out on a quarter technical scale, the minimum share of the reducer was 17.5% by mass.

The analysis of the chemical composition of the samples obtained in the first stage shows that the average carbon content is within the range of 2.55 - 4.30% by mass. The carbon contained in the metal is not a problem - iron alloys with such a carbon content can successfully find a recipient. In the case of silicon in the residual alloy, maximum contents of 1.9 wt% were observed. In the case of alloying elements such as manganese, chromium, nickel, the maximum contents were respectively 2.6, 0.92, 0.5 wt.%. The maximum content of undesirable components, such as phosphorus and sulfur, are respectively: 0.442 and 0.240% by mass. On the other hand, the maximum recorded copper content is 0.464% by mass.

On the other hand, the analysis of the chemical composition of the samples obtained in the second stage showed that the average carbon content was in the range 1.73 - 5.4% by mass. In the case of silicon in the residual alloy, the maximum contents of 1.64 wt.% Were observed. In the case of alloying elements such as manganese, chromium, nickel, the maximum contents were 7.97, 3.21, 0.49% by mass, respectively. The maximum content of undesirable components, such as phosphorus and sulfur, are respectively: 0.07 and 0.240% by mass.

Significant amounts of alloying elements were found in iron alloys obtained in quarter-technical conditions. In the case of harmful and undesirable elements, higher amounts apply to samples obtained in laboratory tests.

It should be noted that the content of specific elements in the iron alloy will depend on the chemical composition of the dust, the reduction conditions and the process. Therefore, during production, the chemical composition of the resulting metallic alloy should be controlled on an ongoing basis, which will allow for its possible modification and classification. This will allow the requirements of end users to be met.

5. CONCLUSION

The analysis of iron alloy obtained as a result of the processing of steel dust was carried out. The analysis was carried out with a view to examining the possibility of its use for the production of certain types of steel. The tests were carried out in laboratory conditions and on a quarter-technical scale. In the case of iron alloys obtained in quarters technical conditions, favorable contents of both alloying elements as well as harmful and undesirable elements were found. In the production technologies of alloy steels, the specification of the charge (scrap) is often used in terms of specific ranges of the content of individual elements, so the obtained iron alloy can be treated as the charge material. This may particularly apply to the production of certain grades of alloy steels. The use of the obtained alloy may translate into lower production costs. The authors developed a technology of waste-free processing of steel dust, which results in ZnO oxide, environmentally neutral slag and iron alloy (C, Mn, Si, Cr). The obtained alloy in an integrated system is directed to the ladle furnace, where the chemical composition is controlled and its possible modification to commercial alloys. The obtained product is cast in a form depending on the recipients' requirements, e.g. in the form of ingots.

ACKNOWLEDGEMENTS

Funding: This research was funded by the National Centre for Research and Development, grant number POIR.01.02.00-00-0089/19. The APC was funded by the National Centre for Research and Development and P.P.H.U. STILMAR.

REFERENCES

[1] LIN, X., PENG, Z., YAN, J., LI, Z., HWANG, J.-Y., ZHANG, Y., LI, G., JIANG, T. Pyrometallurgical recycling of electric arc furnace dust. *J. Clean. Prod*. 2017, vol. 149, pp. 1079–1100.

[2] LOAIZA, A., CIFUENTES, S., COLORADO, H.A. Asphalt modified with superfine electric arc furnace steel dust (EAF dust) with high zinc oxide content. *Constr. Build. Mater.* 2017, vol. 145, pp. 538–547.

[3] RIEGER, J., COLLA, V., MATINO, I., BRANCA, T.A., STUBBE, G., PANIZZA, A., BRONDI, C., FALSAFI, M., HAGE, J., WANG, X., et al. Residue Valorization in the Iron and Steel Industries: Sustainable Solutions for a Cleaner and More Competitive Future Europe. *Metals.* 2021, vol. 11, pp. 1-23.

[4] MACHADO, J.G.M.S., BREHM, F.A., MORAES, C.A.M., DOS SANTOS, C.A., VILELA, A.C.F., DA CUNHA, J.B.M. Chemical, physical, structural and morphological characterization of the electric arc furnace dust. *J. Hazard. Mater*. 2006, vol. 136, pp. 953–960.

[5] CHEN, W.S., SHEN, Y.H., TSAI, M.S., CHANG, F.C. Removal of chloride from electric arc furnace dust. *J. Hazard. Mater*. 2011, vol. 190, pp. 639–644.

[6] LI, C.L., TSAI, M.S. A crystal phase study of zinc hydroxide chloride in electric-arc-furnace dust. *J. Mater. Sci.* 1993, vol. 28, pp. 4562–4570.

[7] QUIJORNA, N., DE PEDRO, M., ROMERO, M., ANDRÉS, A. Characterisation of the sintering behaviour of Waelz slag from electric arc furnace (EAF) dust recycling for use in the clay ceramics industry. *J. Environ. Manag*. 2014, vol. 132, pp. 278–286.

[8] GALCHINETSKII, L.P., GALKIN, S.N., RYZHIKOV, V.D., RYBALKA, I.A., VORONKIN, E.F., LALAYANTS, A.I., STARZHINSKII, N.G., SILIN, V.I. Chemical interaction in the ZnSe-ZnTe-Se-H2-C system. J. Environ. Manag. 2014, vol. 143, pp. 208–213.

[9] VOGELBACHER, M., KELLER, S., ZEHM, W., MATTHES, J. Advanced Methods for Kiln-Shell Monitoring to Optimize the Waelz Process for Zinc Recycling. *Processes.* 2021, vol. 9, pp. 1-15.

[10] MUICA, V.-T., OZUNU, A., TÖRÖK, Z. Comparative Life Cycle Impact Assessment between the Productions of Zinc from Conventional Concentrates versus Waelz Oxides Obtained from Slags. *Sustainability*. 2021, vol. 13, pp. 1-17.

[11] ZHANG, M., LI, J., ZENG, Q., MOU, Q. An Experimental Study on the Reduction Behavior of Dust Generated from Electric Arc Furnace. *Appl. Sci.* 2019, vol. 9, pp. 1-11.

[12] HUDA, N., NASER, J., BROOKS, G., REUTER, M.A., MATUSEWICZ, R.W. Computational fluid dynamic modelling of zinc slag fuming process in top-submerged lance smelting furnace. *Metall. Mater. Trans. B.* 2012, vol. 43, pp. 39–55.

[13] WU, C., CHANG, F.-C., CHEN, W.-S., TSAI, M.-S., WANG, Y.-N. Reduction behavior of zinc ferrite in EAF-dust recycling with CO gas as a reducing agent. *J. Environ. Manag*. 2014, vol. 143, pp. 208–213.

[14] GARCÍA-BAÑOS, B., CATALÁ-CIVERA, J.M., SÁNCHEZ, J.R., NAVARRETE, L., LÓPEZ-BUENDÍA, A.M., SCHMIDT, L. High Temperature Dielectric Properties of Iron- and Zinc-Bearing Products during Carbothermic Reduction by Microwave Heating. *Metals*. 2020, vol. 10, pp. 1-15.

[15] WILLMS, T., ECHTERHOF, T., STEINLECHNER, S., AULA, M., ABDELRAHIM, A., FABRITIUS, T., MOMBELLI, D., MAPELLI, C., PREISS, S. Investigation on the Chemical and Thermal Behavior of Recycling Agglomerates from EAF by-Products. *Appl. Sci*. 2020, vol. 10, pp. 1-14.

[16] WARZECHA, M., HUTNY, A., STRADOMSKI, G., MAŁECKI, S., GARGUL, K., JAROSZ, P., DOBRZYŃSKI, M. Sposób Odzysku Cynku i Stopu Żelaza z Pyłów Hutniczych. Patent Application (PL) P. 424985, 2018.