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Exploring Efficiencies: Examining the Possibility of Decreasing the Size of the Briquettes Used as the Batch in the Electric Arc Furnace Dust Processing Line

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Abstract: Sintering of well-prepared briquetted mixtures in a shaft furnace is one of the possible methods of electric arc furnace dust (EAFD) utilization. Simultaneously, some metal oxides from exhaust gases can be separated. In this way, various metals are recovered, particularly zinc. As a result, zinc-free briquettes are produced with a high iron content, which can be used in the steelmaking process. This method is still being developed. In Ostrowiec Świetokrzyski, Poland, a prototype line of a new method for the reduction of zinc oxide in a shaft furnace with simultaneous sintering of briquettes was installed. The batch for the shaft furnace was actually briquetted in the roller press, which produces briquettes with a volume of 13 cm^3. It may prove beneficial to reduce the size of the resulting briquettes, as a smaller size could prove more efficient in reducing zinc in the furnace. Decreasing the volume of the briquettes causes an increase in the power consumption in the drive system and brings an increase in the briquetting force, which occurred in the compaction zone. It could be harmful to the roller press construction. The aim of this article was to prove that decreasing the volume of briquettes of the EAFD mixtures had no negative effects on the roller press which was installed in the prototype line.

Keywords: EAFD processing; briquetting; EAFD briquette; zinc recovery; briquetting conditions

1. Introduction

One of the by-products of the steelmaking industry is electric arc furnace dust (EAFD) [1–4]. Due to containing some heavy metals (e.g., zinc, cadmium, copper, or lead) this kind of waste has been classified as hazardous [5–7]. Steel scrap, which is commonly delivered to steel mills, is largely coated with zinc, due to the fact that zinc is being used when galvanizing sheets for car production and other steel products like cans, fences, roofing, etc. [8,9]. It is estimated that about 50% of the world production of zinc is used for galvanizing steel components, which prolongs their life three- to fivefold. It can be assumed that the zinc content of the dust in steelmaking will constantly grow [10]. Dust from electric arc furnaces contains an average of 30–40% zinc and around 20% iron. During the production of each ton of steel in an electric arc furnace about 15–25 kg of EAFD is generated [11]. It is necessary to remove zinc from EAFD to recycle it properly [12–15]. Due to the high content of zinc in steelmaking dusts, new methods of dust removal were developed [16]. The method of EAF dust utilization consists of sintering of well-prepared briquetted mixtures in a shaft furnace and simultaneously separating metal oxides from the exhaust [17]. This method allows recovery of EAFD metals, particularly zinc. The ZnO in briquettes made of EAFD mixtures reacts with the carbon present in sinter, reduces to Zn, and, due to high vapor pressure, evolves as gas and exits in the shaft gas phase. The zinc then oxidizes back to ZnO and is collected in the dedusting devices. As a result, zinc-free briquettes are produced with high iron content. These briquettes can then be used in steelmaking processes [18–21]. The prototype line of EAFD recovery was developed in Ostrowiec Świętokrzyski, Poland. In the line, a roller press is used. In the roller presses, the material is continuously compacted between two synchronous and counter-rotating rollers with cavities. The main advantages of a roller press for agglomeration of fine-grained materials are the continuous work with relatively low energy consumption, and the longer lifetime of the forming elements compared to other briquetters, e.g., screw or piston presses. At the moment, only those briquettes produced in the roller press with a volume of 13 cm^3 are subjected to sintering [22]. The conditions of the sintering process need to be optimized. It is also necessary to check how the briquettes with smaller volumes will behave during sintering. Smaller briquettes obtain a larger outer surface area in relation to their bulk density. This can have a positive effect on the sintering process. However, it is required to do the calculations to check whether installing the forming rollers with a smaller forming cavity for producing briquettes of reduced volume will not adversely affect the operation of the roller press installed in the line [23]. Contrary to the roller mills [24] decreasing the volume of the briquettes can cause an increase in power consumption in the drive system, and entails raising the briquetting force taking place in the compaction zone [25,26]. This increased force can prove dangerous for the roller press construction. The aim of this article was to prove, based on laboratory tests and simulations, if the PW500 roller press installed in the EAFD recovery line (Figure 1) would not be overloaded after the installation of the rollers with a smaller volume of the briquettes. The PW500 roller press was equipped in the main motor drive with a 55 kW gearbox, which could slow down to 11.5 RPM rotation speed of the rollers, and a hydraulic system, which supported the unfixed roller with a force of 1000 kN [27].

Figure 1. A view of the PW500 roller press installed in Ostrowiec Świętokrzyski, Poland.

2. Materials and Methods

To examine the loads occurring in the PW500 roller press after reducing the volume of cavities, a computer simulation program of a roller press was used. The simulator was developed by the employees of the Department of Manufacturing Systems of AGH University of Science and Technology, based on the Hryniewicz mathematical model of briquetting in a roller press [28]. The model used the thin layer method. This method consisted, in the separation in the compaction zone, of the volume elements of the briquetted material limited by the side surfaces of the rollers, their sealings, and two planes perpendicular to the direction of the material movement, distant from each other by an infinitely small *dy* value. To determine the relationship between unit forces and stresses on the surface of a separated element, the equilibrium condition of the forces acting on it was used. The program allowed determination of the maximal unitary pressure value exerted on the briquettes in the central zone of the molding cavities, also loads caused in a drive and hydraulic system. When performing a simulation test of the briquetting process of a material, it was necessary to determine the material compaction pressure characteristic (ϑ) and the variability of friction static coefficient (μ_s). In this case, the test of material compaction pressure characteristic (ϑ) and the variability of friction static coefficient (μ_s) were performed, using a steelmaking EAFD from Rolled Products Division of Steelmaking Industry in Poland. The chemical composition of the dust was Zn (35%), Fe (18%), Cl (9%), Pb (3%), Ca (2.5%), Si (2%), Mn (1.5%), and C (1%) [17]. Coke breeze of grain size under 2.0 mm was used as a high carbon component. For the tests, mixtures were prepared which contained 47.7% of EAFD, 36.7% scale, 7.3% fine coke breeze, 5.5% 80° Bx molasses, and 2.8% calcium hydroxide. The last two ingredients were a binder. Four mixtures were prepared, each with a different amount of water added, to obtain the appropriate moisture. The final moisture of the mixture was then chosen to be within the range of moisture favorable for briquetting of this process, resulting in a moisture in the briquetting material within 3.0%–6.3% [22]. Moisture was determined by the weight method at 105 °C, until a constant weight was obtained. The Vibra AJH 420 CE scale was used. The material compaction characteristic was determined using the ZDM-1 press equipped with a cylindrical close die with a 20 mm internal diameter. The force applied to the punch was continuously increased, up to 44 kN, which corresponded to the 140 MPa compacting pressure. The punch feed rate was 6 mm/min. The punch displacement and the applied force was continuously measured and recorded using the data acquisition system. For each EAFD mixture, the measure was taken seven times. Measurements were averaged for each material moisture. Then, the compaction level was calculated by Equation (1)

$$s = H_p/(H_p - x) \tag{1}$$

where:

s is the compaction level,
H_p is the initial height of the compacted material, and
x is the displacement of the punch.

Based on the measurements, the regression equation of the compaction pressure characteristic on compaction level and moisture was determined with Statistica, using the minimum squares method with a 95% confidence level. It was also determined in the experiments that the minimum pressure necessary to properly consolidate EAFD mixtures could not be less than 25 MPa.

The variability of the external static friction coefficient between an EAFD mixture and the working surface of a roller was performed with laboratory stand STZ-1M (Figure 2). The EAFD mixture sample was a cylindrical briquette formed in a die with a ∅ 20 mm diameter and a height around 5 mm. The 18HGT steel of hardness 55 HRC was chosen as a pair sample. The STZ-1M consisted of two main components: the disc drive and the punch pressure system. The drive system achieved a rotation speed 10.5 RPM, corresponding to the linear velocity between the briquette and working rollers, v = 0.0438 m/s on the average 42 mm friction radius. The tests carried out for the pressure exerted on the briquette equaled 20, 40, 60, 80, 100, and 120 MPa, for the four mixtures. Each mixture was tested 7 times. While working on the results, 4 extreme samples were discarded, and the other ones were averaged for each EAFD mixture.

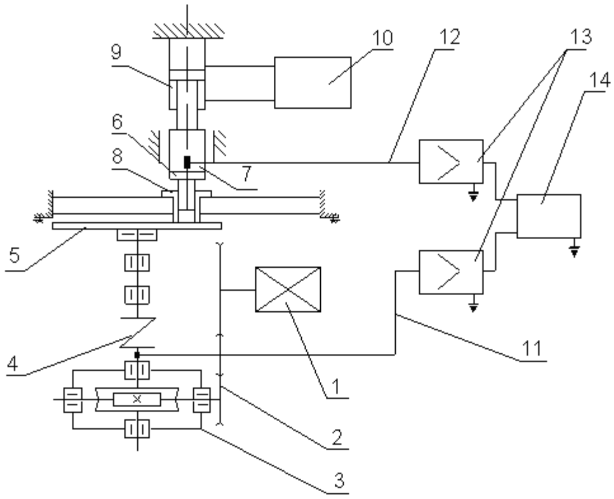
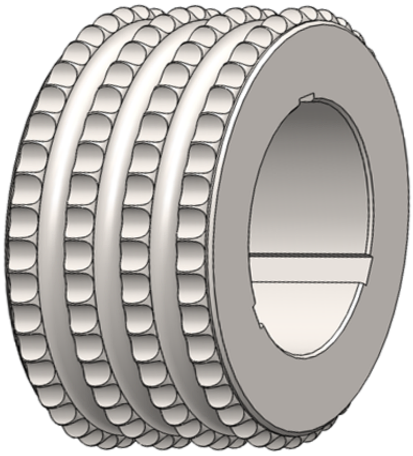


Figure 2. A scheme of the STZ-1M laboratory stand for testing friction in the briquetting process of fine-grained materials: 1—motor, 2—belt transmission, 3—belt gear, 4—clutch, 5—18HGT steel disc, 6—punch, 7—pressure transducer, 8—matrix, 9—hydraulic cylinder, 10—hydraulic system, 11—measuring path of the torque value, 12—measuring path of the pressure value, 13—amplifier, and 14—PC [29].

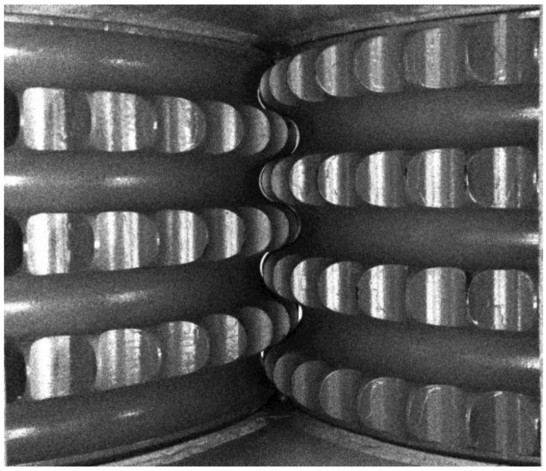
Based on the measurements, the regression equation of the variability of the friction coefficient on compaction level and moisture was determined with Statistica, using the minimum squares method with a 95% confidence level.

The grip angle was determined using the laboratory roller press with a 450 mm pitch diameter of the rollers. Rollers with cavities to obtain a saddle-shaped briquette with 6.5 cm^3 volume and dimensions of $31 \times 30 \times 13$ mm were installed. Briquetting tests of the EAFD mixtures with 3.0%, 5.0%, and 6.8% moisture content were then performed. During the tests, a maximum briquetting pressure in the forming cavity was measured. It was realised by measuring the force acting on the 9 mm diameter pin installed in the bottom of the forming cavity. In the pressure measuring system, the pressure acting on the pin was transferred into the tensometric strain sensor, from which the measured signal was transmitted by NI DAQmx controllers in NI SCXI modular data acquisition kit to the NI_USB-6251 data acquisition module and PC. Data were recorded by LabView. The grip angle was determined in such a way that the results of the computer simulation and the average pressure measured in the roller press LPW450 during briquetting adjusted to the same value [30].

Originally installed in the PW500 roller press were rollers with a 500 mm pitch diameter and a 270 mm width, with the 294 cavities distributed in the 7 rows of 42 cavities each, allowing them to produce a saddle-shaped briquette with 13.0 cm^3 volume and dimensions of $37 \times 37 \times 17$ mm (Figure 3). A new set of rollers with a smaller cavity volume was designed in SolidWorks. The diameter and the width of the rollers were not changed. Decreasing of cavity volume caused change in the rows and cavity numbers. The parameters of the redesigned roller ring are presented in Table 1.



(a)



(b)

Figure 3. The working rollers originally installed in the roller press PW500, (**a**) model created in the SolidWorks program and (**b**) the view down to compaction unit.

Table 1. The parameters of the rollers designed with reduced volume of the cavities.

Briquette Volume (cm^3)	Briquette Size (mm)	Number of Rows	Number of Cavities in the Row	Total Number of Cavities
13.0	37 × 37 × 17	7	42	294
10.5	34 × 34 × 16	7	45	315
8.5	32 × 32 × 15	8	48	384
6.5	30 × 29 × 14	9	52	468

3. Results and Discussion

The moisture for the EAFD mixtures for compaction pressure characteristic (ϑ) and variability of friction coefficient (μ_s) were 2.5%, 3.5%, 4.5%, and 5.5%. The results of compaction level tests are shown in Figure 4. All the compaction pressure characteristics were progressive. It confirmed that EAFD mixtures were adequate for consolidation in a roller press. For briquetting pressures over 25 MPa, all the characteristic were linear. It corresponded with the minimal pressure to obtain a solid briquette. The lowest compaction level was obtained for the EAFD mixture with 2.5% moisture content. The obtained cylindrical briquettes from that mixture in the tests were the most brittle compared to the rest. The highest compaction level was the 4.5% moisture content EAFD mixture. The difference between the lowest and highest compaction level rose with the increase in briquetting pressure. The highest difference was noticed for the 140 MPa pressure, amounting to 19.7%.

The regression equation of compaction characteristics on compaction level and moisture describes Equation (2)

$$\vartheta = 7.785508\ s^{4.304809}\ w^{-0.939358} \tag{2}$$

where:

ϑ is the compaction pressure characteristic,
s is the compaction level, and
w is the moisture content.

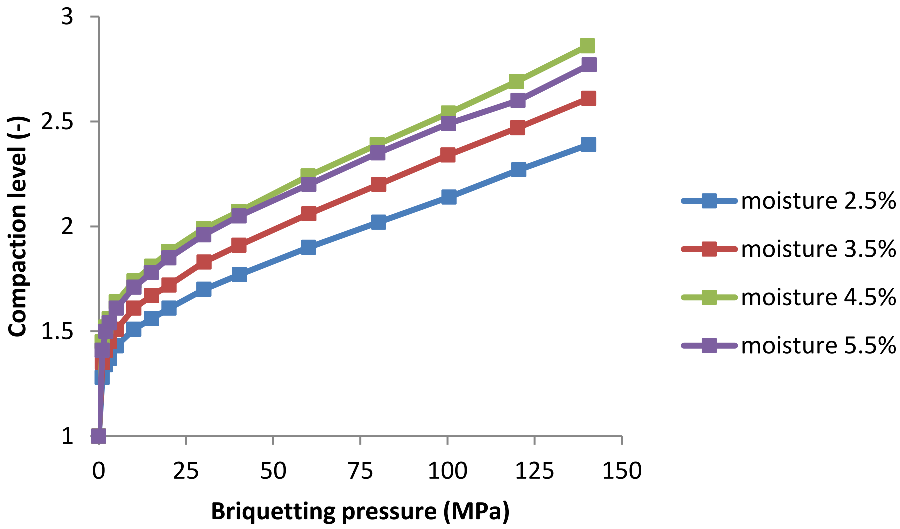


Figure 4. The compaction level with the briquetting pressure for electric arc furnace dust (EAFD) mixtures of different moisture contents.

The example course of friction force in time obtained in the STZ-1 stand for the EAFD mixture is shown in Figure 5. The calculated results of the variability of the friction coefficient tests is shown in Figure 6. Analyzing the characteristics, it could be seen that in each case, the coefficient of external static friction decreased with an increase in briquetting pressure. The EAFD mixture with 2.5% moisture content was characterized significantly different from the others, because it had the highest friction coefficient for each briquetting pressure. The EAFD mixture with 4.5% moisture content had a higher external friction coefficient than the 3.5% mixture. However, with increasing briquetting pressure, the characteristics intersected at 40 MPa, and then the highest value was the 3.5% moisture content mixture. The EAFD mixture with 5.5% moisture content, among the tested mixtures, was characterized by the lowest values of the friction coefficient.

The regression equation of the variability of friction coefficient on compaction level and moisture describes Equation (3)

$$\mu_s = -0.525828s - 0.001754w + 1.501769 \tag{3}$$

where:

μ_s is the coefficient of static friction,
s is the compaction level, and
w is the moisture content.

The example of briquetting pressure characteristics in the forming cavity is presented in Figure 7. The value of the maximum measured briquetting pressure decreased with increases in the moisture content. In Table 2, the value of the grip angle is presented. Based on the results, the average 5.16° grip angle was determined and used in the simulation for the PW500 press. For the simulation 2.0°, the elastic expansion angle was used [30]. The maximum power consumption was calculated based on no changes in the drive system and a constant roller rotation speed at 11.5 RPM. The calculation was based on 90% efficiently of the drive system.

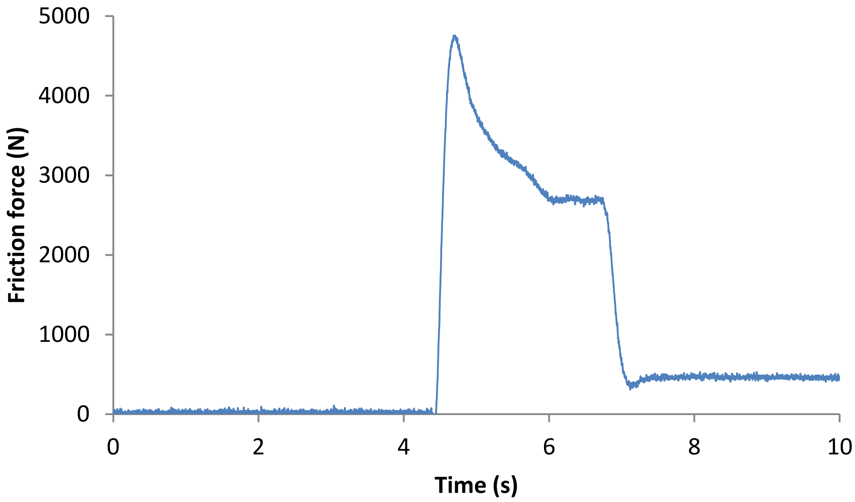


Figure 5. The course of friction force in time for the EAFD mixture with 2.5% moisture content under the 20 MPa pressure obtained in STZ-1 stand.

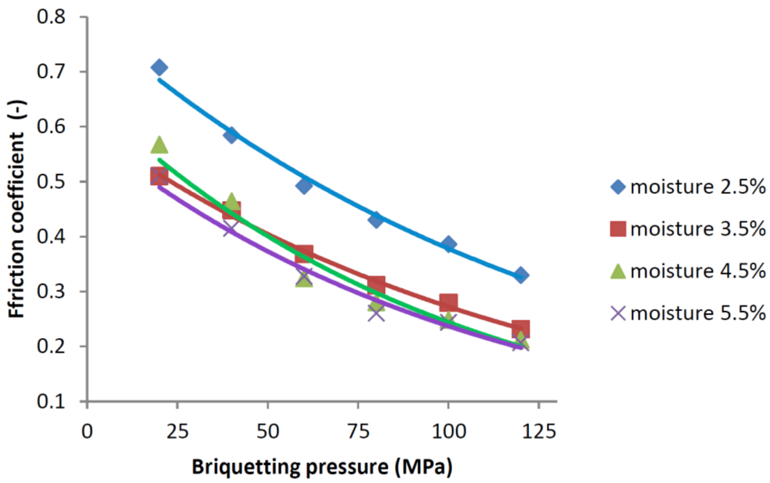


Figure 6. The friction coefficient with the briquetting pressure for EAFD mixtures of different moisture contents.

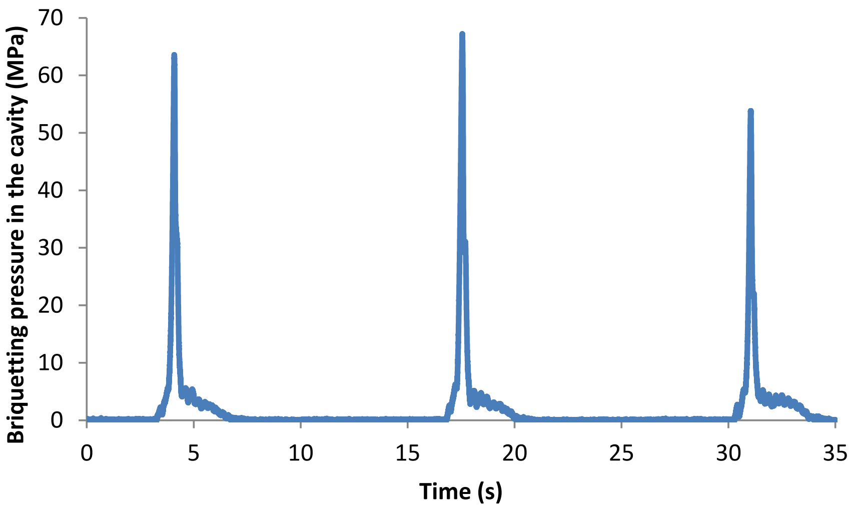


Figure 7. The course of unit pressure in the forming cavity during briquetting of the EAFD mixture with 5% moisture content.

Table 2. The measured maximum briquetting pressure in the cavity and calculated grip angle.

Moisture Content of EAFD Mixture (%)	Maximum Measured Briquetting Pressure (MPa)	Average Maximum Measured Unit Pressure (MPa)	Grip Angle (°)
3.0	73.1, 78.3, 67.9	73.1	4.82
5.0	63.4, 66.6, 53.0	61.0	5.29
6.8	51.9, 52.4, 39.6	48.0	5.36

Based on the results presented in Table 3, it could be concluded that the PW500 roller press was correctly selected for EAFD mixture briquetting in the EAFD recovery line. The simulation indicated that maximal value of the pressure in the forming cavity decreased with increasing EAFD mixture moisture. The roller press equipped with the standard rollers (with cavity volume of 13 cm^3) under normal conditions of use (for EAFD mixes with a moisture content in the range of 3.0%–6.3%) had a power surplus of 57%, taking into account the installed 55 kW motor drive. However, such a large power surplus resulted from the fact that it is a pilot line and also intended for large-scale experiments. Drying the EAFD mixture down to a value of 2% resulted in an increase of maximum pressure, force, torque, and power. The same resulted from a reduction of the gap between rollers. As predicted, reducing the volume of briquettes increased energy demand and the force exerted between the rollers.

Table 3. The results of simulations on decreasing the cavities in the PW500 roller press.

Briquette Volume	EAFD Mixture Moisture (%)	Gap Between Rollers (mm)	Maximum Pressure (MPa)	Maximum Force (kN)	Maximum Torque (Nm)	Maximum Power Consumption (kW) *
13.0	3.0	2	46.9	226.7	14785	19.7
13.0	2.0	2	68.4	330.4	21506	28.7
13.0	3.0	1	57.1	275.7	17807	23.7
13.0	2.0	1	83.2	401.6	25891	34.5
13.0	4.5	2	32.3	155.9	10195	13.6
13.0	6.3	2	23.7	114.6	7514	10.0
10.5	3.0	2	60.4	292.9	18869	25.2
10.5	2.0	2	88.0	425.7	27430	36.6
10.5	3.0	1	76.7	370.7	23631	31.5
10.5	2.0	1	111.7	539.6	34331	45.8
8.5	3.0	2	61.9	299.3	19301	25.7
8.5	2.0	2	90.1	435.8	28057	37.4
8.5	3.0	1	78.9	381.2	24268	32.4
8.5	2.0	1	114.8	554.8	35254	47.0
6.5	3.0	2	70.2	339.8	21793	29.1
6.5	2.0	2	102.1	494.7	31669	42.2
6.5	3.0	1	91.7	443.3	28014	37.4
6.5	2.0	1	133.4	644.9	40680	54.2

* assumed 90% propulsion system efficiency.

4. Conclusions

This article presented an analysis of reducing the PW500 roller press briquette volume. The briquetting machine was installed in an EAFD utilization line. The line consisted of sintering of well-prepared briquetted mixtures in a shaft furnace and simultaneously separating metal oxides from the exhaust. This method allowed recovery of EAFD metals, particularly zinc. Smaller briquettes obtained a larger outer surface area in relation to their bulk density. This reduction in briquette size could have a positive effect on the sintering process.

The PW500 roller press simulation of the maximum pressure, force, torque, and power during the briquetting process was conducted. They showed that the PW500 roller press was correctly selected for the pilot line. The simulation results showed that, for normal roller press conditions (EAFD mixture moisture content in the range of 3.0%–6.3%), it was possible to reduce the size of the briquettes down to a volume of 6.5 cm^3. In all the simulations carried out, their results were lower than 55 kW (installed in the press motor drive power) and 1000 kN (force of the hydraulic system supports the unfixed rollers). However, for a reduced briquette volume down to 6.5 cm^3, long-term operation of the briquetting machine with a small gap between the rollers (1 mm) and in conditions of over-dried EAFD mixture (down to 2%) could be dangerous for the press. According to the results obtained in the simulation, the roller press worked then with practically the maximum possible energy demand of 54.2 kW. This might result in the overheating of the drive system. An interesting direction of the future research may also be the determination of the impact of briquette porosity on the sintering process. The obtained results may also be useful for determining the parameters of the roller press to obtain briquettes of higher porosity.

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