

# Influence of the size of hematite and magnetite ores on the parameters of the sintering process and the quality of the sinter

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**Abstract.** Laboratory sintering of sinter charge based on hematite and magnetite iron ores of various sizes was carried out. The purpose of the study was to determine the effect of the type and size of the ore material on the gas permeability of the sintered layer, sintering performance and the need for fuel. The granulometric composition, cold strength, strength during recovery, and reducibility of the resulting agglomerate have been studied. Differences in the course of the process of agglomeration of hematite and magnetite ores at different sizes were revealed in the research. The established patterns have practical interest from the point of view of increasing the efficiency of the sintering process, improving the quality of the sinter and reducing the harmful impact on the environment.

## 1 Introduction

Along with magnetite ores, hematite ores are of significant value for ferrous metallurgy. Analysis of the mineral resource base of mining and metallurgical enterprises [1-3] indicates the prospects of their use to expand industrial reserves of iron-containing raw materials. However, the technology of their agglomeration has characteristic features that distinguish them from traditional magnetite raw materials [4,5]. Thus, the ability of hematite materials to pelletize in the composition of sinter charges is, as a rule, worse in comparison with magnetite ones, which is associated both with the low wettability of hematite and with the peculiarities of the surface structure of ore grains. Sintering of hematite ores requires increased heat consumption compared to the processing of magnetite ores and concentrates. This is due to the absence in hematite ores of a powerful internal heat source from the oxidation of FeO magnetite, as well as a higher temperature of the beginning of their melting [6].

Analysis of the results of studying the process of agglomeration of iron ores [7-10] showed that, despite the vast amount of information on the patterns of formation of the structure, mineralogical and phase composition of iron ore agglomerates, there is no single point of view either on the mechanism of formation or on the influence of individual factors on qualitative characteristics of iron ore sinters. This circumstance makes it necessary to study the conditions for obtaining iron ore sinter from hematite ore, depending on its size.

## 2 Purpose and tasks of research

The purpose of this study is to establish and compare the regularities of changes in the indicators of the sintering process and the quality of sinter from the size of hematite and magnetite ores and sinter charges based on them. To achieve this goal, the following tasks were set:

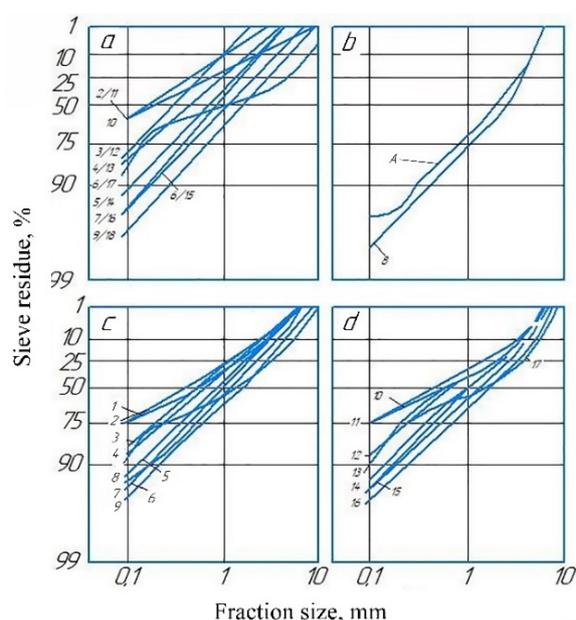
- determination of the influence of the size of ores and sinter charges on their gas permeability;
- determination of the influence of the size of ores and sinter charges on the productivity of sintering;
- determination of the dependence of the demand for solid fuel on the size of ores and sinter charges and the type of ore;
- determination of the influence of the size of ores and sinter charges on the strength of the finished sinter in the cold state, during recovery and on the recoverability.

## 3 Data and methods

To determine the effect of the type of ore, the study did not use a mixture of different ores, but two separate ores - ore A, containing 100 wt.% magnetite, and ore B, containing 94 wt.% hematite. For the experiments, both ores were scattered into six fractions. By mixing the individual fractions, various grain compositions were prepared. Figure 1, a shows the size of the mixtures of fractions of the individual ores. Table 1 shows data on the chemical composition of the individual fractions of the studied ores, and table 2 - data on the chemical composition of the mixtures.

When mixing the fractions, it was proceeded from the fact that the distribution of the mixture by size was as close to normal as possible, as is usually observed in ores and after their grinding. This normal distribution in double logarithmic coordinates is expressed by straight lines. In the area known from industrial studies of the spread of the upper limits of the size and maximum fractions of fines for sinter ores, the composition of the mixtures was expressed by straight lines. Only in one case (experiments 8 and 17) there was no normal distribution; the composition of the mixture was expressed as a curved line. Upon further graphic evaluation of the data, the location of the points for these mixtures was somewhat different from the usual one.

The proportion of the -3 mm fraction in the prepared mixtures ranged from 0–36 wt.%, the -0.1 mm fraction - within 2.7–37.0 wt.%. The maximum grain size of the ore was 10 mm.



**Fig. 1.** Distribution of ore, return and sinter charge according to the size of fractions: a) mixtures of fractions of ores A and B; b) return for ores A and B; c) sinter charge based on ore A; d) sinter charge based on ore B. 1-9 - a mixture of fractions from ore A; 10-18 - a mixture of fractions from ore B

**Table 1.** Chemical composition of the fractions of the studied ores.

Fraction, mm	Substance, wt.%				
	Fe	Fe <sup>2+</sup>	SiO <sub>2</sub>	CaO	MgO
Magnetite ore A					
10-6	67.37	22.41	2.84	0.10	0.90
6-3	64.42	22.61	2.92	0.10	1.04
3-1	66.77	22.46	3.32	0.10	0.88
1-0.2	64.98	19.46	4.66	0.25	1.14
0.2-0.1	67.60	20.70	2.64	0.70	1.14
-0.1	61.19	20.37	6.63	1.44	2.32
Hematite ore B					
10-6	65.18	1.00	3.18	0.10	0.05
6-3	65.13	1.40	3.24	0.10	0.05
3-1	65.23	1.30	3.08	0.10	0.09
1-0.2	65.27	1.40	2.44	0.10	0.09
0.2-0.1	67.51	1.70	1.44	0.10	0.07
-0.1	63.82	1.25	6.10	0.10	0.28

To characterize the mixtures, the HS<sub>50</sub> index was used – this is the mesh size of the strainer through which 50 wt.% of the mixture passes.

The iron content in all agglomerates was maintained at 58 wt.%. The basicity of all agglomerates (CaO / SiO<sub>2</sub>), in turn, was maintained at 1.3, which was achieved by adding dolomite or ground limestone with a particle size of 0–3 mm. The MgO content in the finished agglomerate was to be 1 wt.%. The return addition was constant at 40 kg/100 kg ore. By varying the coke consumption, each experiment was carried out so that the return balance (the ratio of the return yield R<sub>A</sub> to the return flow R<sub>B</sub>) was 95–105 wt.%. The quality of additives and coke, as well as their size, were kept constant.

**Table 2.** Chemical composition of experimental mixtures of fractions, wt.%.

experience	Fe	SiO <sub>2</sub>	CaO	MgO
Magnetite ore A				
1	64.28	4.86	0.74	1.54
2	65.19	4.90	0.73	1.56
3	65.14	4.41	0.48	1.28
4	65.45	4.20	0.43	1.21
5	65.93	4.20	0.43	1.21
6	65.95	3.90	0.26	1.06
7	66.06	3.82	0.24	1.06
8	66.73	3.31	0.35	1.10
9	66.46	3.56	0.19	1.02
Hematite ore B				
10	65.41	4.36	0.10	0.15
11	65.13	4.00	0.10	0.16
12	66.10	2.77	0.10	0.11
13	65.86	2.94	0.10	0.11
14	65.94	2.76	0.10	0.09
15	65.85	2.73	0.10	0.09
16	65.68	2.88	0.10	0.09
17	65.89	2.77	0.10	0.08
18	65.55	2.94	0.10	0.08

All experiments were carried out in a bowl with a suction area of 400×400 mm. The bed was a return with a size of 10–20 mm. The total height of the sintered layer was 300 mm. The vacuum during all experiments was kept constant at 800 mm of water. art. All mixtures were pelletized before being loaded into the bowl. The mixture was ignited at a temperature of 1150 °C. The duration of the experiment was considered the time from the start of ignition to reaching the maximum temperature of the exhaust gases plus 1 min. The agglomerate was then cooled by suction and dropped three times with a height of 2 m onto a steel plate. After dropping, a 6.3 mm square sieve was sieved to determine the return yield.

Sieve and chemical analyzes were performed for all finished agglomerates with equalized return balance. Then the agglomerate was subjected to drum tests, the destruction of the grains at the beginning of the reduction was investigated, and the recoverability was also determined.

## 4 Research results and discussion

When evaluating the research results, it turned out that the

return size fluctuated greatly. For each ore, based on all sieve recovery analyzes, a mixed sieve analysis was calculated, which is graphically presented in fig. 1, b. It was found that the return during sintering of hematite ore B has fewer fine fractions than the return during sintering of magnetite ore A.

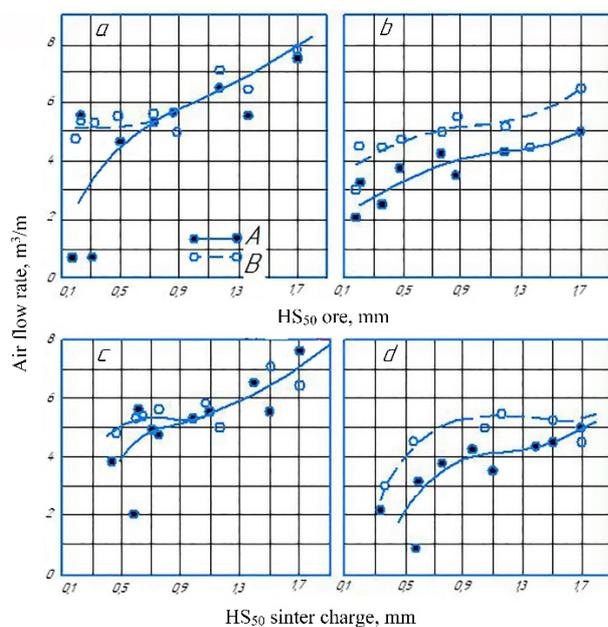
The oxidation state of the return in individual experiments also fluctuated. It was determined by calculation. When using ore A, it was 94%, when using ore B - 97.3%. Thus, the dependence of the oxidation state of the return on the oxidation state of the charge is visible.

Since the return flow rate of 40 kg/100 kg of ore mixture was kept constant, the return had a significant effect on the properties of the entire mixture. In this regard, in fig. 1, c, d shows the size of the entire charge A and the entire charge B. In contrast to pure ores, significant changes are visible. All sieving curves are biased towards larger fractions.

As already mentioned, when graphically evaluating the research results for the characterization of ore mixtures or mixtures with return, it seemed most appropriate to use the  $HS_{50}$  indicator. In some cases, the best indicator was the content of the fraction  $-0.1$  mm. The graphical assessment of the measurement results in all cases was carried out, firstly, in relation to the size of the ore used, and secondly, in relation to the size of the entire charge. The need for the latter is caused by a strong change in the size of the charge due to the addition of return.

#### 4.1 Gas permeability of the charge in the sinter bowl

Fig. 2, a, b and d show the gas permeability of the sinter charge in the bowl as a function of the size of the ore and the entire charge. The intake air flow rate was measured before ignition and at the time corresponding to 60% of the sintering time.



**Fig. 2.** Dependence of the gas permeability of the charge in the bowl on the size of the ore and sinter charge: a), c) before igniting the charge; b), d) after 60% of the sintering duration.

For both ores, a shift in  $HS_{50}$  values towards larger fractions was established during the transition from ore to agglomeration. Before ignition, in all cases, an increase in gas permeability is observed with an increase in the grain size (Fig. 2, a).

For finer mixtures, there is a difference between the gas permeability of ores A and B: the gas permeability of ore B is higher than that of ore A. about 5 m<sup>3</sup>/min, and for ore A - only 3 m<sup>3</sup>/min.

The best gas permeability of hematite ore is observed when the particle size is  $HS_{50} = 0.7-0.8$  mm or for the size of the entire charge  $HS_{50} = 0.9-1.0$  mm. It was also found that for hematite ore these values in the area of fine fractions fluctuate strongly. The same picture is observed for the second moment of time (Fig. 2, b, d).

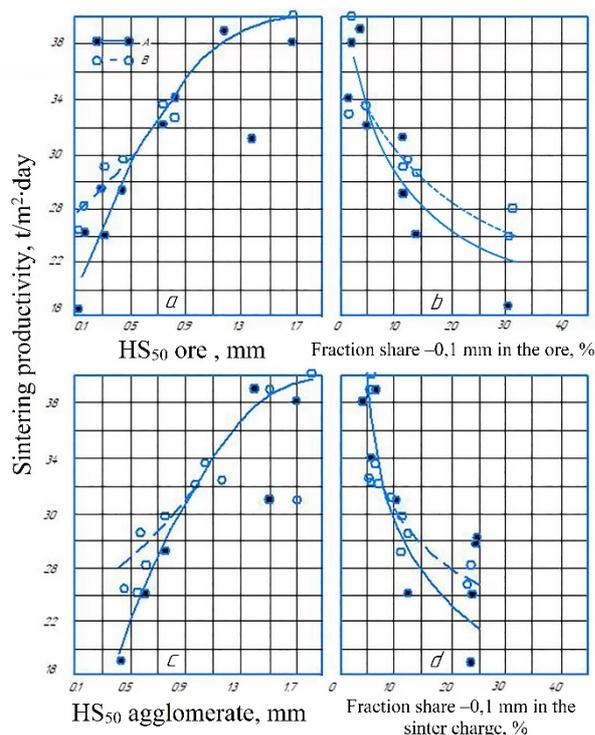
If in the area of coarse fractions these values lie very close to one another, then in the area of small fractions they differ significantly. The scatter area for ore A is also larger in this case. It was also found that the gas permeability of hematite ore in the area of very fine fractions by the second selected time point decreases much less than that of magnetite ore.

The higher gas permeability when using hematite ore can be explained by the greater strength of the lumps due to the adhesive components. With strong waterlogging of the sinter charge in the lower part of the bowl, less strong destruction of the formed lumps occurs here than during sintering of the charge from magnetite ore.

#### 4.2 Sintering performance

Fig. 3 shows the dependence of the sintering performance on the size of the ore and sinter charge. Here, along with the  $HS_{50}$  index, the fraction content of  $-0.1$  mm was also used as a parameter. As expected, sintering productivity increased with increasing ore size. At the same time, the difference between hematite and magnetite ore was not established. The achieved productivity was 40 t/m<sup>2</sup>-day. In the same way as for gas permeability, differences between the two ores were found for the sintering performance in the area of fine fractions (Fig. 3, a and b). These differences are found when the value of the  $HS_{50}$  index for ores starting from 0.6 mm and for the entire charge starting from 1.0 mm, which coincides with the corresponding data for gas permeability.

With this method of assessment, the indicators with a fractional composition that did not correspond to the normal distribution (experiments 8 and 17) were very different from the rest of the data. Therefore, an estimate was adopted for the content of the fraction  $-0.1$  mm. Fig. 3, b and d, it is clearly seen that with an increase in the fraction of  $-0.1$  mm, productivity decreases. The difference is again noticeable for ores A and B in the area of fine fractions, and for ore - starting with a fraction of  $-0.1$  mm 5 wt.%, and for the entire charge - starting with a fraction of  $-0.1$  mm 7 wt.%. These differences can also be explained by the different lumpiness of the ore. It should be emphasized once again that all experiments were carried out with the same return content in the charge.



**Fig. 3.** Dependence of the productivity of sintering on the size of the ore and sinter charge

### 4.3 Moisture mixture

The moisture content of the mixture was determined by manual test. Upon subsequent determination of the moisture content, it was found that, as expected, it decreases with increasing grain size. However, the charge from hematite ore was found to have a significantly higher moisture content. It was 6.0–7.5 wt.%, and in the charge of magnetite ore – only 4.0–5.6 wt.%. From this it is seen that hematite ore in the area of fine fractions has a larger specific surface area than magnetite.

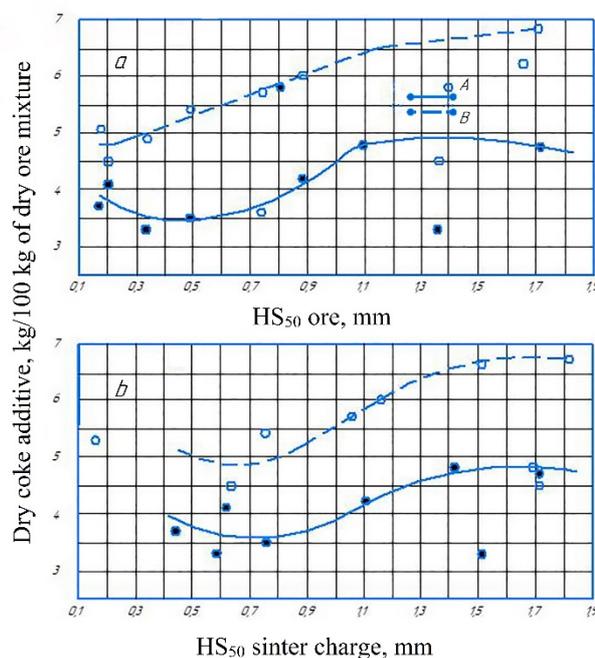
### 4.4 Fuel requirement

Fig. 4 shows the dependence of the demand for dry coke on the size of the ore and sinter charge. At the same time, there is a noticeable difference in the demand for coke for magnetite and hematite ores. On the other hand, the influence of the ore size is noticeable.

Starting with a certain grain size, the need for coke is constant or increases very slightly. Thus, with the value of the indicator  $HS_{50}$  for ore 1.1 and above, the need for coke for hematite ore B is 6.7 kg/100 kg of dry ore, and for magnetite ore - 4.7 kg/100 kg of dry ore (Fig. 4, a).

The corresponding value of the  $HS_{50}$  indicator for the whole charge is 1.4 mm. With a smaller grain size, the need for coke in both cases decreases to a sharp minimum (especially for sinter charge), which is in the range of values of  $HS_{50} = 0.6-0.7$  mm (Fig. 4, b). This minimum, related to the size of the ore, is sharply expressed for magnetite ore and is at a value of  $HS_{50} = 0.5$  mm. In the area of even smaller fractions, a marked increase in the demand for coke was again found, both for magnetite and

hematite ores.



**Fig. 4.** Dependence of the need for coke on the size of the ore and sinter charge

### 4.5 Size of the finished agglomerate

The sieve analysis of the finished agglomerate clearly depends on the size of the sinter charge, but even in this case there are differences for hematite and magnetite ores. Fig. 5 shows the dependence of the content of the fraction +25 mm in the agglomerate on the index  $HS_{50}$ . In the area of smaller fractions, the points for hematite and magnetite ores are located closer to each other and in both cases in this area the data scatter is larger.

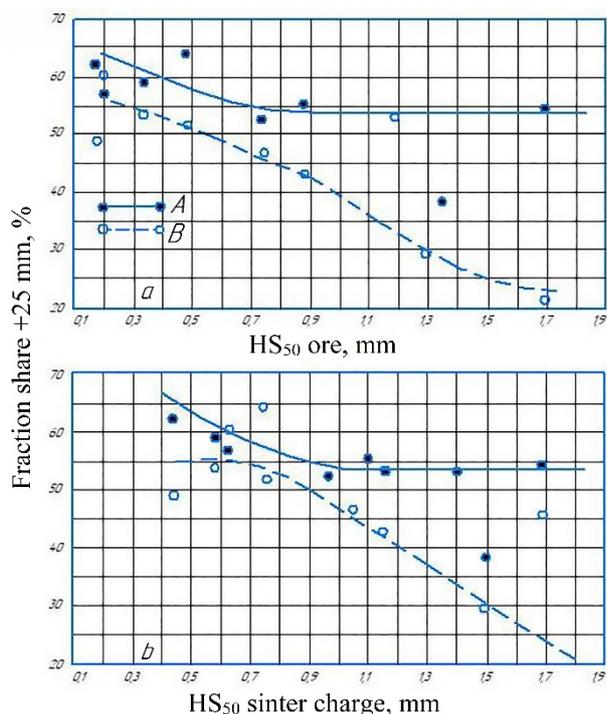
With an increase in the size of hematite ore B, a continuous decrease in the yield of the agglomerate fraction of +25 mm is observed, while for magnetite ore A, starting with an  $HS_{50}$  of 0.8 mm (for a sinter batch of 1.0 mm), this value remains constant. In general, the yield of the +25 mm fraction in the agglomerate from magnetite ore is higher than from hematite, which indicates their different sintering capacity.

### 4.6 Drum strength

An agglomerate sample weighing 15 kg was loaded into a drum 1000 mm in diameter and 500 mm in length and ground in 200 revolutions at a rotation speed of 25 rpm. After that, sieving was carried out into fractions +6.3 and -0.5 mm. The proportion of the +6.3 mm fraction characterizes the drum strength, the proportion of the -0.5 mm fraction characterizes abrasion.

Tests have shown that the abrasion of the agglomerate from hematite ore is 7.6–5.3 wt.% and there is a tendency to decrease it with an increase in the size of the ore. For agglomerate from magnetite ore, abrasion is 8.0–6.4 wt.%, and in this case there is also a tendency to decrease it with

an increase in the size of the ore. The maximum abrasion was observed at an  $HS_{50}$  value for a charge of 0.6–0.7.



**Fig. 5.** Dependence of the +25 mm fraction content in the finished agglomerate on the size of the ore and sinter charge

Fig. 6 shows the dependence of the drum strength (fraction yield + 6.3 mm) on the size of the ore and charge. It should be noted that the strength of 41–53 wt.% for agglomerate from magnetite ore and 46–58 wt.% for sinter from hematite ore cannot be considered satisfactory. These results can be explained by the basicity of the fluxed agglomerate at the level of 1.3, which often leads to a decrease in strength indicators.

However, attention is drawn to the fact that agglomerates from magnetite ore A and from hematite ore B have different strength values and the nature of its dependence on the size of the ore and sinter charge. In the agglomerate of magnetite ore A, with an increase in size, an increase in strength is first observed to reach a maximum at  $HS_{50} = 0.6$  mm for the ore and 0.8 mm for the charge. Then, with an increase in size, a constant decrease in strength is observed, and in the area of the largest fractions, the strength indicators turn out to be lower than in the area of the smallest fractions.

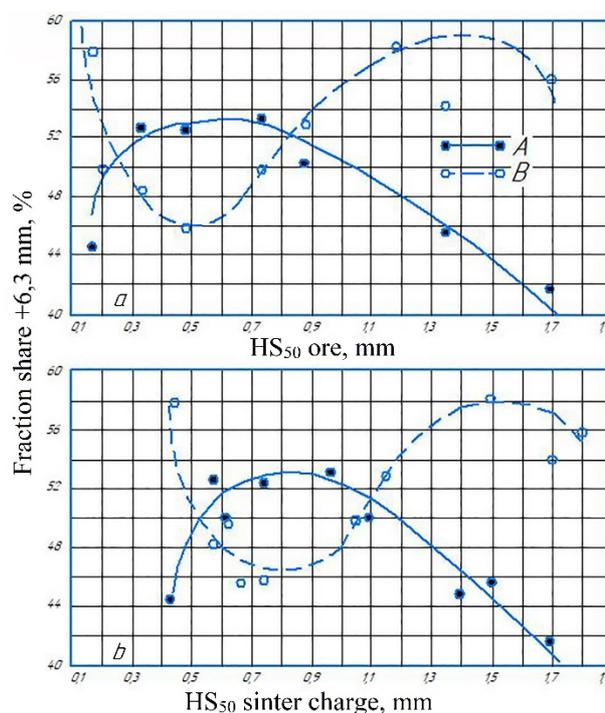
In contrast to this, in hematite ore sinter B, the strength has a minimum at  $HS_{50} = 0.5$  mm for the ore and 0.8 mm for the sinter charge. With an increase in the size to the value  $HS_{50} = 1.4$  mm for ore and 1.5 mm for sinter strength, the strength increases to a maximum and then decreases again.

Both extremes of strength in both the smallest and the largest fractions are expressed equally sharply.

#### 4.7 Reduction behavior and influence of the oxidation state

As known from the results of other studies [7], the

agglomerate at a temperature close to 500 °C, in weakly reducing conditions, tends to especially strong destruction. To obtain data on the strength of the agglomerate during the reduction process, the following test was carried out: an agglomerate with a size of 12.5–16 mm in an amount of 500 g was loaded into a rotary kiln with an inner diameter of 150 mm and a length of 540 mm with an external electric heater. The speed of rotation of the furnace was 10 rpm. The oven has four 20 mm high plates. Inside the sample was heated for 40 min with a reducing gas consisting of 24 vol.% CO; 16 vol.% CO<sub>2</sub>, and 60 vol.% N<sub>2</sub>, up to 500 °C. The exposure at this temperature was 1 h. Then, in a stationary furnace, the sample was cooled with nitrogen to 400 °C, and then with air access. After the end of the experiment, the sample was dispersed according to the size class of +6.3 mm and –0.5 mm. The degree of agglomerate reduction was calculated from the weight loss.



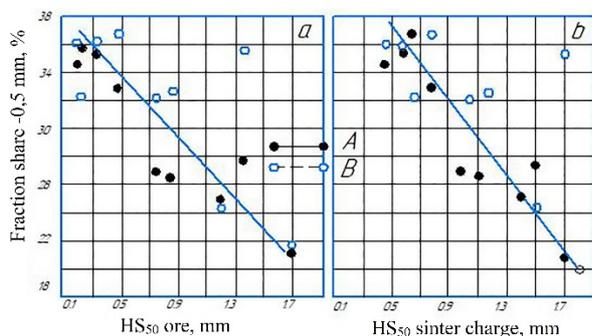
**Fig. 6.** Dependence of drum strength on the size of ore and sinter charge

The recovery test showed that all the resulting agglomerates under these conditions were more or less destroyed. So, for agglomerate from magnetite ore A, the residual content of +6.3 mm fractions was 0.2–5.3 wt.%, and from hematite ore B - 0.7–14.4 wt.%. These data are very unsatisfactory and are also explained by the basicity of agglomerates 1.3, at which they have a high tendency to destruction under weakly reducing conditions.

Fig. 7 shows the dependence of agglomerate abrasion on the size of the ore and sinter charge. At the same time, a decrease in abrasion is seen with an increase in the size of the ore or batch.

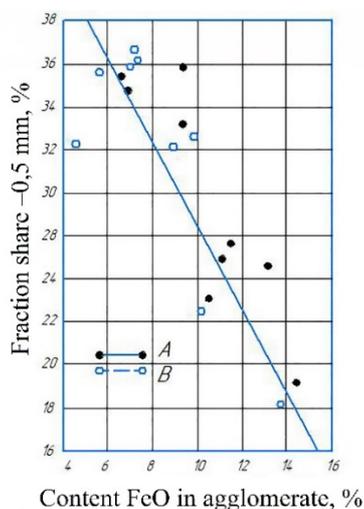
No differences were found between magnetite and hematite ores. The points for both ore grades are evenly spaced around the straight line. When determining the dependence of abrasion on the content of the fraction –0.1

mm, it was found that when the content of this fraction is more than 10 wt.%, the abrasion remains constant even at very unfavorable values (32 wt.%) and decreases only when the content of the fraction  $-0.1$  mm is below 10 wt.%.



**Fig. 7.** Dependence of the destruction of the agglomerate at the beginning of recovery on the value of  $HS_{50}$

As already mentioned, under these conditions, the demand for coke with an increase in size increases. However, at the same time, the FeO content in the finished agglomerate also increases. Fig. 8 it can be seen that with an increase in the FeO content, abrasion decreases. It can be assumed that this influences the improvement of abrasion with increasing particle size.

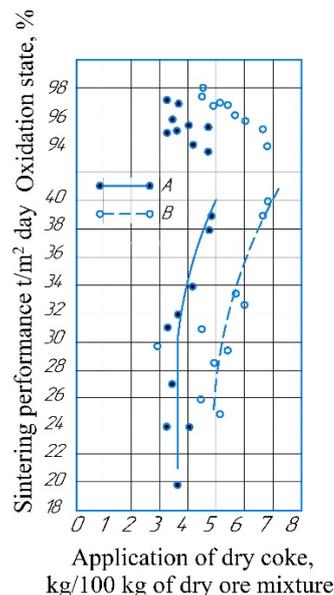


**Fig. 8.** Dependence of agglomerate destruction at the beginning of recovery on the FeO content

The sintering performance, as expected, clearly depends on the coke consumption. In fig. 9 clearly shows the difference in the demand for coke when using hematite and magnetite ores. To achieve the same productivity, this requirement for both ores differs by 1.5–2 kg of coke/100 kg of ore mixture.

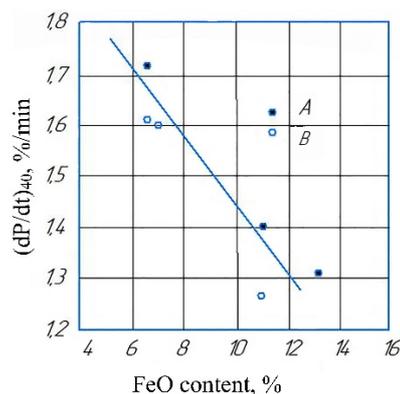
The demand for coke also determines the FeO content or the oxidation state of the agglomerate. With the same fuel consumption, the oxidation state of sinter from hematite ore B is 2–3% higher than sinter from magnetite ore A. However, since the demand for coke for magnetite ore with the same size of sinter charge is about 1.5–2 kg lower than for hematite, the oxidation state of the finished

agglomerate, as can be seen from fig. 9, with a corresponding change in the consumption of coke in both cases is the same and does not depend on the content of magnetite in the sinter batch.



**Fig. 9.** Dependence of the sintering performance and the oxidation state of the agglomerate on the demand for coke

The agglomerate was tested for reducibility at a reduction temperature of 1000 °C with simultaneous loading of the sample. The amount of oxygen withdrawn was measured in wt.%/min at a reduction rate of 40%. The obtained indicators of recoverability can be considered very high. For both ores, with an increase in the grain size, a certain decrease in reducibility is noticeable. But since with an increase in particle size, the need for coke increases, and thereby the FeO content in the finished agglomerate, fig. 10 shows the dependence of the recoverability on the FeO content.



**Fig. 10.** Dependence of reducibility on the FeO content in the agglomerate

With an increase in the FeO content in the agglomerate, the reducibility decreases. It is also seen that the reducibility of agglomerates from magnetite and hematite ore mixtures is the same.

## 5 Conclusions

Experiments on sintering artificially obtained mixtures of fractions from magnetite ore A and hematite ore B made it possible to reveal a number of features of this process depending on the grade and size of the ore. In particular, it can be concluded that:

- the gas permeability of the layer and the sintering productivity increase with increasing size for both ores. Only in the area of very fine fractions was there a difference between hematite and magnetite ore.

- better gas permeability and higher productivity of sintering in the area of fine fractions for hematite ore can be explained by better lumpiness of the charge due to the higher content of adhesive components;

- the minimum need for fuel was observed at an average particle size;

- the best values of the drum strength of the agglomerate were obtained with different sizes of hematite and magnetite ores, and the nature of the change in drum strength from the size differs significantly for these ores;

- a certain increase in strength charge an increase in the size of both ores or sinter mix was observed with an increase in the FeO content in the agglomerate;

- the oxidation state of the sinter at the same size and a certain predetermined consumption of coke is the same for both the hematite ore sinter and the magnetite ore sinter.

The established patterns will make it possible to optimize the granulometric composition of the sinter mixture, which will lead to an increase in the efficiency of the sintering process, namely, to a decrease in solid fuel consumption, which, in turn, will reduce the harmful effect on the environment by reducing CO<sub>2</sub> emissions. In addition, improving the strength of the agglomerate will reduce the formation of dusty fractions (<0.1 mm) during shipment and further transportation to the consumer.

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