Development of steelmaking slag processing scheme for environmental stress reduction

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Abstract. The paper proposes a method of processing steelmaking slag in order to save resources. The authors propose to include partial granulation of steelmaking slags in the processing scheme. This option includes draining the slag melt from the steelmaking unit into ladles and dividing the slag melt into two parts, one of which is enriched in iron. The resulting product can be recommended for use in construction, in agriculture as fertilizers, as well as as a slag-forming flux in steelmaking. During the experiments, the possibility of pyrometallurgical reduction of iron from metallurgical slag was revealed. The influence of the reduction temperature on the yield of iron from the slag is established.

1. Introduction
When smelting cast iron and steel, a large amount of technological waste is generated. Of these, up to 80% falls on slags, which are formed from waste rock of iron ore materials, fluxes, fuel ash, as well as metal oxidation products and impurities. The largest is the output of blast furnace slag - per 1 ton of pig iron, it is 0.5–0.7 tons, the smallest - when smelting steel in electric furnaces - 0.1–0.04 tons [1].

More than 350 million tons of slag from blast-furnace, steel-smelting, foundry and ferroalloy production are accumulated in slag dumps of the Russian Federation. The area occupied by dumps exceeds 2.2 thousand hectares [2]. As a rule, dumps, located in the city limits, near metallurgical plants, disrupt the landscape, occupy land, and worsen the ecological situation [3, 4].

Slag dumps have a significant negative impact on the condition of nearby rivers and other water bodies. This is manifested primarily in the form of changes in the chemical composition of water and bottom sediments [5].

Transition to market relations in many factory towns of the Urals gave a start to the primary processing of slag dumps. Basically, this is sorting and magnetic separation in order to extract metal (the iron content in the slag is about 1.5%) and sifting on screens to produce slag crushed stone. The cost of slag gravel is 1.5-3.0 times lower than that of gravel from natural raw materials.

At large enterprises, the slag of the current blast furnace production is currently almost completely processed, and advanced processing technologies are used [6]. After granulation of the fire-liquid slag, it serves as a raw material for the production of slag Portland cement (SPC) and lime-cementing materials, can be a fine aggregate of concrete and mortars based on these binders. Granulation is an obligatory step, since with rapid freezing of the melt the necessary mineralogical composition of the material is formed, containing the maximum amount of active vitreous phase. SPC is obtained by joint grinding of Portland cement (PC) clinker, granulated slag and gypsum or by thorough mixing of these
materials, crushed separately. The cost of SPC when 30-60% granular slag is introduced into the mixture is 1.5-2.0 times lower than PC from mineral raw materials.

Slags of current steel production are processed mainly into crushed stone. They are not exposed to deeper processing. This is due to the high melting point of steelmaking slags and their quick hardening after release from the furnace unit. Therefore, it is not possible to granulate them similarly to domain ones.

The development of technologies for the deep processing of dump and steelmaking slags will create conditions for the complete processing of slag from current production and reduce the area of slag dumps, which will improve the environment. On the other hand, this will solve the problem of building binders in places where there are slag dumps without natural raw materials.

Currently, in Russia and abroad, work is underway to find rational methods for the processing of steelmaking slag in a liquid state by granulation. For this purpose, a variety of plant designs are used, water, steam and air are used to cool the melt and as an energy carrier [7, 8].

It has been experimentally proved that steelmaking slags that have passed the granulation stage sharply reduce hydraulic activity and a tendency to self-decay. In terms of chemical and mineralogical composition, heat-crushed steel slags are closer to Portland cement than blast-furnace slags and can serve as raw materials for the production of building binders.

The main difference between steelmaking slag and Portland cement is the content of iron and manganese oxides, as well as the presence of sulfur. Thus, with a decrease in oxidation and sulfur content in steelmaking slags, the possibilities of their application expand: as the basis for slag-forming mixtures in the steel industry; for the production of Portland cement and other construction binders, as well as fertilizers or active wastewater filters.

We have analyzed various methods of granulation of steelmaking slags.

Sintering granulation of steelmaking slags did not find application due to the high concentration of metal in the slag discharged from the furnace. This led to an unstable granulation process: pops and sharp emissions of the vapor-gas mixture when metal enters the water. The second negative factor was the constant sweeping of the swinging lattice-screen. The third and main negative factor is the significant difficulties in placing a pool of water in the immediate vicinity of the steelmaking unit.

Out-of-furnace granulation in special plants separated from steelmaking units at a distance of 1.5 to 5 km was not found due to the low overheating of the slag melt above the solidification onset temperature. The final slag discharge temperatures in that period were 1530–1550° C, and the beginning of slag solidification was 1350–1280° C [9].

Currently, the process of releasing steel and slag from smelting units is carried out at temperatures of 1600–1650° C. Slag is poured into slag ladles at temperatures of 1600–1650° C, and the modern steelmaking process is characterized by high intensity: metal and slag are drained almost immediately after the melt has been purged with oxygen. The separation of liquid metal and slag is not perfect - the slag emulsion gets into the slag bowl. With further sludge, separation occurs into liquid metal, which settles to the bottom of the bowl and liquid slag. The practice of steelmaking slag processing at OJSC “MMK” shows that the slag in slag bowls received for processing after 60-80 minutes. after release from the oven, retains the ability to provide release.

2. Experimental part

The research objectives included development of a scheme for metallurgical slag processing and determining the temperature ranges for the recovery of slag from ferrous metallurgy and the exposure of melts in the furnace, contributing to a more intensive extraction of iron.

After the analysis of granulation options for steelmaking slags, it was decided to granulate them in the laboratory. The research was carried out in the laboratory of the department of metallurgy of ferrous metals of Nosov Magnitogorsk State Technical University in Tamman resistance furnace.

In steelmaking slags, the sulfur content is from 0.7 to 1%. In water granulation of slag, regardless of the design of the aggregates, the process occurs by abrupt cooling of molten slag with water. Upon contact of the melt with water, its intense evaporation occurs.
The smell of hydrogen sulfide during granulation was felt. But the water into which the slag was poured did not change the pH. This is due to the fact that, in parallel with the formation of the acidic products H₂S and SO₂, CaO hydration occurs, followed by neutralization of the acidic compounds with alkali. As a result of the experiment, a black product was obtained, which crumbled under a slight mechanical effect. The resulting product can be recommended for use in construction, as a result of hydration, it is more resistant to destruction, in agriculture as fertilizer, and also as a slag-forming flux in steelmaking.

Thus, it is proposed to include partial granulation of steelmaking slag in the processing scheme.

Liquid steelmaking slag in ladles is delivered to the granulation unit in 40-60 minutes after draining from the smelter. This time is sufficient to separate the slag-metal emulsion, but at the same time, the mobility of the melt is maintained. After installation, the slag ladles begin to turn over, and it is necessary to drain into the pool only 30-40% of the melt in the ladle. This will avoid the discharge of metal into the pool, which will affect the quality of the resulting granular product. The rest of the molten slag with settled metal is sent for further processing. The concentration of iron in the remainder of the slag melt increases, which will increase the recoverability of the metal during processing.

The product obtained after granulation and drying (granular steelmaking slag) contains a minimum amount of sulfur, iron and manganese, in addition, it is obtained without a crystalline structure, therefore it can be used as lime-containing material for slag formation in the metallurgical process and for the production of slag Portland cement and other binders building materials.

To capture steam and gas emissions, we suggest installing a shelter with a common steam and gas outlet and sending it to the organizational cleaning system in oxygen-converter shops. Shelter must be equipped with electric shutter gates [7].

Thus, we propose a method for processing steelmaking slag in order to save resources. This option includes draining the slag melt from the steelmaking unit into ladles and dividing the slag melt into two parts, one of which is enriched in iron. Drainage is carried out at a temperature above 1600 °C, at which blasting slag melt is blown with air at an air flow rate of 4-5 m/min; after emptying, the buckets are fed to a granulation unit, where the aforementioned separation of slag melt into two parts is performed by draining from the ladle into a pool of 30-40% slag melt to obtain a granular product, after which the remaining part in the ladle, enriched in iron, is fed for further processing to extract iron, while the slag melt in the ladle after being drained from the steel mill before dividing it into parts is sedimented for 40-60 minutes.

The proposed scheme for the processing and use of metallurgical slag in existing production is shown in figure 1.

![Figure 1. Proposed slag processing scheme.](image-url)
The type of granulation plant should provide for the disposal of water vapor containing more sulfide compounds. The drum granulation method is most suitable for this requirement.

After loosening slag by special machines on a caterpillar track, it is sent to pyrometallurgical processing, after which molten pig iron and recovered slag are obtained.

The second part of the research was to determine the temperature ranges for the reduction of slag and the holding of melts in the furnace, contributing to a more intensive extraction of iron.

To conduct an experiment on reducing iron in a Tamman resistance furnace, weighed 150 g of slag were taken, which were loaded into graphite crucibles. The chemical composition of the original slag is presented in Table 1.

| Material          | Chemical composition, % |
|-------------------|-------------------------|
|                   | CaO | SiO₂ | FeO | MgO | P₂O₅ | MnO |
| Converter slag    | 34.2| 15.7 | 28.8| 13.2| 0.59 | 4.1 |
| Open-hearth slag  | 21.9| 15.5 | 39.4| 9.7 | 0.69 | 4.5 |

When conducting thermodynamic analysis, it was found that a more intense extraction of iron will contribute to an increase in the temperature of the process. Therefore, it was decided to study the original slag (Table 1) at various slag reduction temperatures (Table 2).

| Material                       | Chemical composition, % | Degree of recovery K, % |
|--------------------------------|-------------------------|-------------------------|
|                                | CaO | SiO₂ | FeO | MgO | P₂O₅ | MnO | Degree of recovery K, % |
| Converter non-magnetic product | 45.5| 16.8 | 4.7 | 16.6| 0.35 | 3.45 | 83.7                  |
| Open-hearth non-magnetic product | 37.6| 22.2 | 10.8| 14.4| 0.81 | 5.15 | 72.6                  |
| Converter non-magnetic product | 45.6| 16.7 | 4.6 | 16.5| 0.33 | 3.43 | 84                   |
| Open-hearth non-magnetic product | 37.9| 22.1 | 10.7| 14.5| 0.8 | 5.16 | 72.8                 |
| Converter non-magnetic product | 45.8| 16.9 | 4.7 | 16.6| 0.34 | 3.42 | 83.7                 |
| Open-hearth non-magnetic product | 38.0| 22.0 | 10.7| 14.7| 0.81 | 5.17 | 72.8                 |
| Converter non-magnetic product | 45.9| 16.9 | 4.5 | 16.8| 0.33 | 3.43 | 84.3                 |
| Open-hearth non-magnetic product | 38.2| 22.0 | 10.6| 14.5| 0.80 | 5.15 | 73                   |
| Converter non-magnetic product | 46.1| 16.9 | 4.5 | 16.7| 0.32 | 3.44 | 84.3                 |
| Open-hearth non-magnetic product | 38.3| 22.1 | 10.5| 14.6| 0.81 | 5.16 | 73.4                 |
Table 2 shows that the recommended temperature for the recovery of slag is 1600-1650° C.

In the described experiments (table 2), the content of calcium oxides in the reduced slag increases, which leads to an increase in the melt viscosity and a decrease in the rate of iron reduction and the precipitation of metal droplets.

The average degree of recovery is 80% when the melt is held in the furnace for 5-6 minutes. When holding for 15 minutes, the metal yield in the experiment increases by 10%, and when holding for 20 minutes - by 15% (figures 2 and 3).

![Figure 2](image1.png)

**Figure 2.** Exposure of molten converter slag at various temperatures.

![Figure 3](image2.png)

**Figure 3.** Exposure of molten open-hearth slag at various temperatures

Figures 2 and 3 show that after the melt is held, the FeO content decreases, the degree of metal reduction from slag increases.

### 3. Conclusion

The inclusion of partial granulation of steelmaking slags into the processing scheme will allow for a more comprehensive processing of steelmaking slags, while significantly reducing the negative impact
on the environment and involving more technogenic raw materials in the processing. In addition, the crushing stage is eliminated, which simplifies the process of processing steelmaking slag and reduces economic costs.

The effect of the reduction temperature on the yield of iron from slags was established. The longer the slag melt is kept and the higher the temperature in the range 1300–1650° C, the higher is the degree of metal recovery.

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