Ferroalloy industry waste processing

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Abstract. In order to develop a technology and equipment for remelting waste from the ferroalloy industry, the Yurga ferroalloy plant gives 1500 kg of ferrosilicon waste to “Sibelektroterm” for experimental smelts and formulation of technical requirements for new remelting equipment. The findings of these operations are presented in this article. The results of experimental ferroalloy waste processing smelts in a direct-current furnace with the power of 140 kW are examined; parameters of three-phase electric furnaces of alternating current with power 0.63-6.3 MV·A and technologies of ferroalloy waste processing are examined. In addition, original characteristics of the waste are considered. Remelting of ferrosilicon waste in three-phase alternating current furnaces is considered.

1. Introduction
The cracking and sifting of ferroalloys into commercially viable fractions produce a substantial amount of small particles that are not suitable for sale due to limited consumer value. It is especially true with regard to 75 % of ferrosilicon of less than a 3 mm fraction, the cost of which is 20-30 % lower than that of larger fraction ferrosilicon.

According to the data of the Serov ferroalloy plant, ferrosilicon sifting produces up to 20 % of small and dust-like fractions from the whole ferroalloy production. Ferrosilicon dust is usually either moved by water transport to waste depots, or stored in landfills, thereby markedly polluting the environment. Besides, the transportation of ferrosilicon waste to the landfills and their service require significant expenses. Considering the scale of ferrosilicon production, the amount of such waste grows yearly by approximately 20-30 thousand tons, and now the build-up of ferrosilicon dust is measured by hundreds of thousands of tons. The cost of such material constitutes up to 80 % of the cost of the respective ferrosilicon brand.

The accumulation of ferrosilicon dust in industrial facilities creates preconditions for situations of fire hazard and health damage to the staff. Fused with the atmosphere (moisture in the air), ferrosilicon waste can also emit flammable gases. The quality of finely dispersed ferrosilicon kept in storage deteriorates over time. That is explained by gradual oxidation and pollution of stored material, which leads to a decrease in effectiveness parameters of its further usage.

Under the conditions of market economy, industrial enterprises acutely face the problems of energy and resource conservation. Metallurgical remelting of ferroalloy waste is not only economically profitable, but it also diminishes the number and area of industrial landfills, thus diminishing ecological stress.

In order to develop technology and equipment for the remelting of ferroalloy industry waste, the Yurga ferroalloy plant gave 1500 kg of ferrosilicon waste to “Sibelektroterm” for experimental smelts
and formulation of technical requirements for new remelting equipment. On request of Sibelektroterm, 500 kg of the waste was processed using the experimental equipment of the Lyakishev Research Center for Ferroalloy Industry Technology and Processing of Technological Materials. The results of these operations are presented in this article.

2. Original characteristics of the waste
The chemical composition of the waste is equal to that of high-grade ferrosilicon: silicon content is 74-78%, the fraction is less than 1 mm.

The resulting amount of the 3 mm fraction of 75% ferrosilicon comprises 14-17% and more of the weight of the original ingots. The analysis of the shape of these particles shows that the dust is made up of pointed particles with a linear size of 1-3 mm (50-70%). These are a product of the ingot's mechanical grinding, and rounded particles with a linear size <1 mm (30-50%), which are apparently products of breakdown of low-strength areas of the ingot (mechanophase transformation of lebeauite).

Practical observations have shown instability in distribution of particles with the size of small fractions of ferrosilicon, which changes in the storage process.

For a more exact confirmation of this assumption some 75% ferrosilicon of <3 mm fraction was conditioned in a metallic container for 30 days, and thereafter sifted once again; after which the content of the dust-like small fraction grew from 23% to 34%. During the conditioning, the sample gave off a pronounced garlic smell, and if open fire was put next to it, a yellow flame characteristic of the burning of hydrogen and phosphines emerged.

GOST R 50 422-92 contains the information characterizing fire and explosion hazard of 75% ferrosilicon fractions of less than 3 mm. In particular, the auto-ignition temperature of the emitted mixture of hydrogen and phosphines is 860 °C, and the intensity of gas emission is 30 cm³/(kg·h) from dry particles and 60 cm³/(kg·h) from moist. Consequently, storage of 75% ferrosilicon particles of less than 3 mm fraction creates a high probability of autoignition and gas emissions.

Since dust and small particles from ferrosilicon grinding belong to the category of fire-dangerous and explosive materials, in the present state they are neither suitable for transportation, nor for remelting of any sort.

The incoming control of the examined waste is presented in Tables 1 and 2. Chemical analysis of the material was carried out via x-ray spectroscan Maks-GV.

| Table 1. Fractional composition of the waste |
|---------------------------------------------|
| Content, %                                  |
| 5mm<2.5 mm                                  |
| 2.5-5 mm                                    |
| 1–2.5 mm                                    |
| <1 mm                                       |
| 8                                           |
| 1                                           |
| 46                                          |
| 45                                          |

| Table 2. Chemical composition of the waste |
|-------------------------------------------|
| Content, %                                |
| Si                                        |
| Mn                                        |
| Cr                                        |
| P                                         |
| S                                         |
| Al                                        |
| Ca                                        |
| Ti                                        |
| Fe                                        |
| 78.0                                      |
| 0.5                                       |
| 0.2                                       |
| 0.035                                     |
| 0.005                                     |
| 2.5                                       |
| 0.9                                       |
| 0.2                                       |
| the rest                                  |

3. Remelting of ferrosilicon waste in direct current furnaces
One of the options for economically profitable remelting of ferrosilicon waste is to use a direct current arc furnace (DCAF) as a recycling aggregate. Such furnaces are analogous to arc steel furnaces (ASF) in the design of basic structural elements, as well as scrap loading and liquid metal distribution mechanisms, they utilize the same fireproof materials and allow for the same technological processes for melting and refinement of metal.

Nevertheless, there are also substantial differences in the structural arrangement of the furnace, characteristics of the melting process and the equipment set due to the different nature of physical
interactions of arcs of direct and alternating current with the liquid metal bath. The consideration of these differences allows us to determine the areas of the most effective use of DCAF and ASF [1].

Unlike ASF, DCAF has one vertically positioned roof electrode, which is fixed in the body of the electrode holder and inserted into the operating space of the furnace through an opening in the center of the roof. That makes it possible to make DCAF more airtight than ASF, and ensures a more even heating of the scrap and the lining around the bowl's perimeter (without overheating of the lining opposite the electrodes and lower melting speed on the slopes between the electrodes, as it happens in ASF). Power supply in DCF is provided by a specialized semiconductor direct current source.

DCAF are structurally optimized in terms of speed, in that the direct current transformer is equipped with a high-speed electronic regulator that ensures high stability and independent fine regulation of the current mode on a broad range of furnace arc voltage. Furthermore, the system of furnace control includes a regulator ensuring maintenance of a given level of arc voltage through axial movement of the roof electrode, which changes the arc length, with the time constant of around 300-1500 ms.

Experimental smelts took place in a DCAF with the power of 140 kW, voltage variation range of 0...140 V, current variation range of 0...2000 A.

When a residual amount of molten metal was created, the tests were carried out. Without turning off the power, the furnace was switched to the open arc mode and power was increased to 120 kW with the voltage of 60 V and current of 2 kA. The time of melting reached 40-50 minutes. Then the tap hole would be opened and the molten metal poured into specially prepared lined molds without tilting of the furnace. About 20 % of the smelt was left in the furnace for the next melting by elevating the tap 20 mm higher than the bottom of the furnace.

Table 3 shows the chemical composition of the produced alloy.

| No. of sample | Scrap composition, kg | Weight of the metal, kg | Content, % |
|---------------|-----------------------|-------------------------|------------|
|               | Ferrosilicon| Flux | Si | Al | Ca | Mn | Ti | P |
| 1             | 50.0       | 2.5 | 47.3 | 69.7 | 1.79 | 0.76 | 0.42 | 0.11 | 0.03 |
| 2             | 50.0       | 2.5 | 44.9 | 72.7 | 1.94 | 0.63 | 0.40 | 0.12 | 0.03 |
| 3             | 50.0       | 5.0 | 46.0 | 74.6 | 1.90 | 0.60 | 0.38 | 0.12 | 0.03 |
| 4             | 50.0       | 5.0 | 46.9 | 74.2 | 1.73 | 0.42 | 0.42 | 0.15 | 0.03 |
| 5             | 50.0       | 2.5 | 47.1 | 75.0 | 1.96 | 0.47 | 0.40 | 0.12 | 0.03 |

The waste slag of the last smelt (No. 5) had the following chemical composition, wt. %: 20.7 CaO; 40.4 SiO₂; 32.3 Al₂O₃; 5.9 MgO.

The flux composition included quartzite, lime, and alumina, according to the ratio corresponding to the composition of the waste slag from ferrosilicon FS-75 smelt (CaO 15-20 %; SiO₂ 25-35 %; Al₂O₃ 25-35 %).

Chemical composition of the prepared flux, wt. %: 18.7 CaO; 35.4 SiO₂; 35.8 Al₂O₃; 4.8 MgO.

The chemical composition of the smelted ferrosilicon fits the present GOST 1415-91. It is determined that in the remelted ferrosilicon the content of aluminum is lower by 0.14-0.37 %, calcium by 0.14-0.48 %, titan by 0.09 %.

Calculation of specific energy consumption is carried out for the remelting of ferrosilicon of the following composition:
- 1000 kg ferrosilicon, of which: silicon – 75 %; iron 25 %;
- 50 kg – flux.

The amount of heat necessary for the heating of 1000 kg of ferrosilicon and 50 kg of flux up to the melting temperature:

\[ Q_t = C_p \cdot 1000 \cdot 1450 + C_p \cdot 50 \cdot 1700 = 432225 \text{ kcal,} \]

in which:
$C_p$ – specific heat of ferrosilicon, 0.167 kcal/(kg·°C);
$C_{p1}$ – specific heat of the flux, 0.294 kcal/(kg·°C);
1450 and 1700 °C – melting temperatures of ferrosilicon and flux respectively.
Latent melting heat of ferrosilicon and flux:
$$Q_L = L_p \cdot 1000 + L_{p1} \cdot 50 = 77800 \text{ kcal},$$
in which:
$L_p$ and $L_{p1}$ – melting temperatures of ferrosilicon and flux, 75 and 56 kcal/kg respectively.
Heat spent on overheating of smelting products from melting temperature to 1750 °C is:
$$Q_C = C_p \cdot 1000 \cdot (1750 - 1380) + C_{p1} \cdot 50 \cdot (1750 - 1700) = 74775 \text{ kcal},$$
in which:
$C_p$ and $C_{p1}$ – heat capacity of liquid ferrosilicon and slug, which is 0.2 and 0.31 kcal/(kg·°C), respectively.
Heat losses from the shell and the bottom of the furnace depend on the overall area of a 4.5 MW furnace and is 80 m².
Temperature of the shell is 120 °C; specific heat losses at ambient temperature 25 °C are 1600 kcal/m².
$$Q_4 = 1600 \cdot 80 = 128000 \text{ kcal}.$$
Overall heat loss:
$$Q = Q_1 + Q_2 + Q_3 + Q_4 = 712800 \text{ kcal}.$$
Heat loss from the furnace throat is assumed to be 10 %, therefore the full heat consumption should comprise:
$$Q = 712800 : 0.9 = 792000 \text{ kcal}.$$
The amount of electric energy necessary to provide this amount of heat is:
$$791200 : 860 = 920.07 \text{ kWh/t}.$$
Raw data of determination of productivity of a direct current furnace with the power of 4.5 MW:
nominal capacity is 6 t; transformer power – 4.5 MW; useful power – (4.5 · 0.95) = 4.275 MVA; yearly time of furnace operation is 8160 · 0.85 = 6936 h; 0.85 – the furnace loading coefficient.
Furnace productivity:
- daily (4.275 · 0.92) · (6936 : 365) = 88.3 t;
- yearly (4.275 · 0.92) · 6936 = 32.23 thousand tons.
The construction of the furnace may be executed as the stationary type with taps or the tilting type with a discharge spout. Figure 1 shows a photograph of a DCAF on an assembly stand at Sibelektroterm.
4. Remelting of ferrosilicon waste in three-phase alternating current furnaces

Today small and medium power universal electric furnaces are used for producing special alloys and materials: titanium slags, manganese metal, carbon-free ferrochrome, ferrotungsten, ferromolybdenum, ferrovanadium, and other alloys. Such electric furnaces are basically equivalent to those used for remelting any ferroalloys \[2\]. Table 4 and Figure 2 present their basic parameters and dimensions \[3, 4\].

| Parameter                  | 0.63 MV·A | 1.2 MV·A | 1.5 MV·A | 2.5 MV·A | 6.3 MV·A |
|----------------------------|-----------|-----------|-----------|-----------|----------|
| Voltage range, W           | 42-94     | 52-117    | 57-125    | 67-153    | 95-208   |
| Transformer                | ETMPR-1000/10-UHL4 | ETMNR-2500/10-UHL4 | ETMNR-2500/10-UHL4 | ETZNS-5000/10-UHL4 | ETCNR-12500/10-UHL4 |
| Electrode diameter, mm     | 200       | 250       | 250-300   | 300-350   | 450-500  |
| Shell diameter, mm         | 1700-2100 | 2900-3500 | 3200-3800 | 3600-4200 | 4400-5200 |
| Shell height, mm           | 1500-1800 | 2500-2900 | 2500-2900 | 2700-3100 | 3200-3700 |

Dimensions of the furnace

| Length, mm | Width, mm | Height, mm |
|------------|-----------|------------|
| 9000       | 4000      | 5800       |
| 11000      | 4400      | 6000       |
| 11900      | 4500      | 6000       |
| 12800      | 5500      | 6500       |
| 15500      | 7000      | 8600       |

Electric furnaces are quite universal \[5-7\]. They allow smelting a broad variety of alloys without any substantial changes to the furnace construction and workshop infrastructure and with minimal retraining of the staff.

The remelting of ferroalloy waste can be carried out in both the arc mode and the arc-free slug mode. Increased output of liquid metal, decreased specific electroenergy consumption and increased remelting speed can be expected. Another substantial advantage of such technology is the stability of electric parameters \[8\] and absence of intense noise and smoke emissions \[9\]. Problems of optimization of
electric modes of furnaces are solved, among other things, by balancing the electric parameters of the furnace [10-13].

5. Conclusion
Thus, we can draw the following conclusions.
1. The results of experimental ferroalloy waste processing smelts in direct current furnace with the power of 140 kW are examined.
2. Parameters of three-phase electric furnaces of alternating current with 0.63-6.3 MV·A power and technologies of ferroalloy waste processing are examined

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