Development of scientific and technological bases of processing of cast iron from thermal timing and ladle processing method of the resonant intermittent refining

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Abstract. The paper considers the application of the technology of resonant pulsating refining to improve the quality of cast iron products. This technology is used in the production of molds from pig iron and induction cast iron. It is characterized by comparative simplicity and easily fits into existing production. The effectiveness of this technology is at the level of the best world indicators.

1. Introduction
Currently, the processing of metallurgical waste (magnetized kings of cast iron and steel slag dumps, recycling scrap pallets and molds, etc.) is relevant. These types of waste are characterized by an increased content of sulfur, phosphorus, an unstable structure of cast iron products obtained from a heterogeneous charge, and an increased gas content of the metal. The need for technologies to remove these impurities and gases becomes relevant. Semisynthetic iron smelting technology was developed, including the processing of both cast iron and steel scrap and waste. This technology was distinguished by the production of castings with a stable microstructure and mechanical properties of cast iron and operational performance of products from this cast iron. Such high performance of the products is mainly due to the application of the thermal-melt processing modes in this technology. The methods for determining the optimal temperature regimes were based on the approaches developed in the schools of Samarina A.M., Bauma B.A., Kudrina V.A. and Elansky G.N.

To obtain high quality products, the following tasks were solved: 1. A comprehensive technology has been developed that allows the processing of a heterogeneous metal charge; 2. A method has been developed and introduced to reduce the sulfur content in acidic induction furnaces; 3. A method has been developed to neutralize the harmful effects of phosphorus in gray cast iron; 4. Stabilized the structure and properties of cast iron induction melting by the optimal modes of thermal treatment of
the melt; 5. The gas content of the metal is stabilized before pouring the products by the method of resonantly pulsating metal refining; 6. A mathematical model is constructed for conducting numerical experiments to study the effect of phosphorus on the thermodynamic properties of iron.

In the iron foundry, the problem of increasing the sulfur content in pig iron scrap [1] is becoming more acute every year, reaching a level of 0.17%, as the practice of plants shows. According to the data of [1, 2] over the past 200 years, the sulfur content in cast irons has increased by almost 10 times, which is associated with the use of coke in cast iron for melting. Sulfur removal is a rather complex metallurgical task, the solution of which is associated with considerable costs of energy carriers and reagents, which can lead to higher prices for products, and often makes products unprofitable. All this requires the development and implementation of new resource-saving technologies [3-5], one of which is metal desulfurization in induction furnaces. This is all the more relevant in connection with the appearance in the industry of induction melting plants with wide technological capabilities for producing alloys of ferrous and non-ferrous metals [6-8].

2. Technology description
We have proposed, successfully tested and implemented at a number of enterprises the technology of refining cast iron melt from sulfur with basic slags by the “extraction” mechanism, which was successfully implemented in acid induction furnaces. The essence of technology is as follows. When the crucible of the furnace [9-11] is filled with (60 ... 70)% of the single-circuit metal circulation already exists in the furnace bath, which when the metal is heated to a temperature of 1420° C intensively crushes the slag cover and draws the slag particles deep into the metal. Since the slag particle is drawn deep into the metal, it is shielded by liquid metal from the lining of the furnace. This technique allows the use of basic slags that will not interact with the acid lining. The essence of extraction refining [12] as applied to the desulfurization process is as follows: particles of calcareous slag are drawn by electromagnetic fluxes deep into the induction furnace. The surface layer of slag particles is deoxidized by carbon metal and silicon. As a result, the solubility of sulfur increases dramatically, and the surface layer of slag particles absorbs sulfur from the metal. Further, metal flows carry sulfur-rich slag particles to the surface in contact with the atmosphere of the furnace, where the surface layer of slag particles is oxidized by atmospheric oxygen. As a result, the solubility of sulfur in the surface layer decreases sharply, and, being released from the slag, it is oxidized by oxygen to SO2 and is removed into the atmosphere of the furnace. This process is repeated many times. The sulfur removal mechanism in induction furnaces with acid lining was investigated in the conditions of the foundry of ZSMK OJSC. The experiments were carried out on IChT-10M furnaces when casting iron for casting pallets and heaters. When slagging, it is advisable to use lumpy lime instead of fines. During processing, the pieces of lime do not have time to completely dissolve and do not form a homogeneous slag melt, which, when aged during the loading of slag, may fall on the lining and corrode it. As experiments have shown, such slag does not form during the work with lump lime, which explains the fact that this method of metal desulfurization practically did not affect the stability of the furnace lining. Analysis of slag samples taken during and after desulfurization showed that during processing by this method, slag is usually heterogeneous, consisting of separate small (1 ... 4) mm pieces of lime with a slag surface. Despite this, they provide a high degree of desulfurization.

3. Results and discussion
In order to increase the effectiveness of this technology, statistical methods evaluated the influence of various technological parameters on the rate and degree of metal desulfurization in acidic induction furnaces of industrial frequency. We compare the performance and kinetic parameters of the IChT-10M furnace with industrial (50 Hz) frequency and the average (250 Hz) frequency of the MFTGe6.000 furnace. An analysis of the dependences of the experimental treatment showed that the main influence on the degree of desulfurization of Cdcs of cast iron is exerted by the basicity of the slag and the degree of filling of the Cf crucible (Fig. 1). This is explained by the fact that with decreasing crucible filling, the specific mixing power increases, and this leads to an increase in the
circulation speed of the slag-metal emulsion, which ensures an increase in the degree of metal desulfurization.

![Graph showing the dependence of the degree of desulfurization on the degree of filling of the crucible](image)

**Figure 1.** Dependence of the degree of desulfurization on the degree of filling of the crucible on the IChT-10M furnace.

The influence of various technological parameters on the rate of desulfurization was also evaluated. It was found that the rate of desulfurization is most affected by the degree of filling of the crucible and the initial sulfur content in the melt. As you know, medium-frequency furnaces have a higher specific power, for example, an industrial frequency induction furnace IChT-10M has a specific power when the crucible is completely filled (200 ... 300) kW/tn, when the crucible is not completely filled (400 ... 700) kW/tn, the medium-frequency furnace MFTGe6.000 has a specific power (800 ... 900) kW/tn. Therefore, it is of interest to evaluate the effect of mixing power on the kinetic parameters of metallurgical reactions, in particular desulfurization. The joint results obtained in the induction furnaces IChT-10M and MFTGe6.000 are presented in (Fig. 2).

![Graph showing the effect of specific mixing power on the desulfurization rate](image)

**Figure 2.** Effect of specific mixing power $P_m$ on the desulfurization rate $R_{des}$.

An analysis of these results showed that the rate of desulfurization of cast iron with an increase in the mixing power from (200 ... 300) kW/tn to (850 ... 900) kW/tn increases by an order of magnitude from (0.0005 ... 0.00072) %/min. up to (0.0084 ... 0.0096) %/min. At the same time, there was a significant difference in the change in the rate of sulfur removal with different filling of the crucible in induction furnaces of industrial and medium frequency. So, in induction furnaces of industrial
frequency with the full filling of the crucible, sulfur removal practically does not occur, since inert cold slag floats on the surface of the crucible and does not react with the metal. When the crucible filling is reduced to 80%, the mixing intensity increases significantly, the slag heats up and sulfur is removed according to the classical mechanism during the transition of sulfur from metal to slag floating on the metal surface, while the desulfurization rate is insignificant and does not exceed 0.0005 %/min. When filling the crucible (60 ... 70)% or less, the rate of desulfurization of cast iron changes significantly. This is due to a change in the mechanism of sulfur removal during the transition from classical to extraction metal refining. In this case, the sulfur removal rate increases significantly and reaches 50% 0.00072 %/min when filling the crucible, and 0.0015 %/min at 30%. To assess the development of processes by this mechanism, a study was conducted on the content of SO2 in the atmosphere of the furnace and gas exhaust paths using the universal gas analyzer UG-2. As shown by the balance melts and the study of the gas content in the exhaust gases from the IChT-10M induction furnace, this mechanism removes from 16 to 80% of the removed sulfur, while the specific SO2 content in the exhaust gases increases by almost 3 times. A higher desulfurization value by this mechanism corresponds to a lower filling of the crucible. Under such conditions, slag is not an accumulator of removed sulfur, but an intermediate phase through which sulfur is transported to the gas phase. The use of pig iron desulfurization technology can significantly reduce the sulfur content in pig iron from 0.09-0.17% to an acceptable level of 0.015-0.040% in practice. This allows, as shown by operational tests, to increase the operational resistance of heat-resistant castings (slag for slag formed in the production of aluminum) by 2 times. One-circulation circulation is also advisable to use in the process of smelting cast iron, for example, when alloying cast iron with oxides, such as manganese and vanadium. Innovative technologies in waste processing are a reserve that, with relatively small investments, allows you to create new jobs and reduce the negative impact on the environment. In recent years, EVRAZ ZSMK JSC has developed [13, 14] and passed technical testing and technologies of resonant-pulsating refining of metal (RPR) have been introduced.

![Figure 3. Diagram of tuyeres with a sickle-shaped nozzle (a) and a nozzle with a cylindrical pulsator (b): 1 - refractory pipe; 2 - steel pipe for gas supply; 3 - tuyere tip with a rod; 4 - crescent gap; 5 - cylindrical pulsator.](image)

Physical blowing of a metal with a tuyere with a gas-dynamic pulsator, as shown by physical modeling, is distinguished by the special nature of the outflow of gas into the liquid. It was noted that the depth of jet penetration is much less than when blowing with a sickle lance (high-speed blowing), but more than when blowing through cylindrical nozzles. This technology allows you to simply
control the processing of the melt, introducing the required flow rate of inert gas into the lance, intensifying the processing of the melt. In addition to the low-frequency region, the melt is subjected to processing by a whole spectrum of vibrations from low-frequency to high-frequency [13, 14]. The experimental results showed that melt processing is performed in the range from 1 to 23000 Hz. This technology has been successfully implemented on cast iron of blast furnace and induction melting of metal. It allowed to significantly reduce the gas content of the metal, increase the density of cast iron castings from 6890–6900 to 7000–7200 kg/m³, the mechanical properties of cast iron and the performance of its products. The high efficiency of RPR was demonstrated in the processing of blast furnace pig iron for the production of molds and slag bowls [15].

4. Conclusion
This technology has significantly improved the strength properties of the metal, to neutralize the harmful effects of phosphorus due to changes in the microstructure of cast iron. The operational durability of cast iron products subjected to RPR is at the level of the best domestic and foreign indicators.

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