# Steeling of synthetic cast iron in induction crucible furnace taking into account consumption rate of carburizers

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**Abstract.** In an article about the importance of the choice of materials, harmful impurities in synthetic cast iron, and improving the strength characteristics of cast iron, which requires a new method of smelting synthetic cast iron using steel scrap as charge in the corresponding crucible furnaces, the presence of a charge of metal charge, together with pig iron, the return of own production, carburetors, and ferroalloys for the purpose of carburizing and alloying to the required chemical composition.

## 1 Introduction

The essence of smelting synthetic iron is the metallurgical enrichment of liquid iron with carbon and silicon in arbitrary proportions, as well as the use of high-temperature processing, which makes it possible to obtain alloys with predetermined chemical composition and properties. For the formation of high properties of cast iron in castings, it is necessary to destroy the imperfect structure of the initial charge materials. The use of induction furnaces for smelting synthetic iron makes it possible to carry out deep thermal treatment, refining, modification, and alloying of liquid metal [1].

### 1.1 Objects and methods of research

Induction furnaces have high technological flexibility, i.e., they make it possible to obtain cast iron of any chemical composition, produce liquid metal in arbitrary portions, store metal for a long time without changing its properties, use charge materials of low bulk weight, mechanize and automate smelting processes. To obtain synthetic cast iron, steel, and cast iron scrap, return of own production, sheet trim, shavings, and other low-grade metal waste are mainly used. Currently, the use of metal in mechanical engineering is 70%, i.e.30% of the metal goes to waste, most of which has a low bulk density, making it difficult to further process [2].

The problem of efficient use of metal waste of low volumetric weight is most rationally solved by organizing the smelting of synthetic pig iron. The advantage of such smelting is the possibility of remelting waste directly at the place of their formation - in foundries of machine-building plants without long-term transportation and irretrievable loss of metal.

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Pig irons are generally excluded from the charge composition, which frees up the corresponding capacities of metallurgical production. The use of cheap metal waste for smelting synthetic pig iron reduces its cost by 25-30 % compared to conventional remelted cast irons. It is advisable to use synthetic cast iron to produce high-quality cast irons, especially with nodular graphite, given the low content of demodifying impurities in them [2].

At present, synthetic cast iron is used to manufacture a variety of parts for critical and especially critical purposes, for example, locomotive and wagon blocks, friction wedges, crankshafts, cylinder blocks, internal combustion engine heads, wear-resistant castings, machine casting, etc. operating at high loads and elevated temperatures [3].

The main factor determining the content of the strategy for developing modern foundry production is the use of modern technological processes, especially melting technology. First of all, this concerns the production of cast iron castings, which make up 65% of the mass of all alloys. Since 2000, the amount of pig iron scrap has sharply decreased in Russia, and the cost of cast iron and the cost of their transportation have increased significantly. This led to an increase in material costs in the production of castings from synthetic iron, which was mainly obtained in crucible induction furnaces of industrial frequency (ITF).

In addition, problems began to arise with the use of an acid lining as the cheapest and most durable since an increased amount of steel scrap began to be used in the metal charge, and for this reason, the melting temperature was raised above 1450°C. The durability of the lining has sharply decreased, and the downtime associated with its replacement has increased. All this hurt the production efficiency of castings from synthetic cast iron [4].

Cast iron, the oldest type of black injection molding material, is also currently the most widely used material in the foundry industry. In particular, these are good processing properties (excellent fluidity, low tendency to shrink and their formation, low tendency to stress), as well as acceptable mechanical properties and good machinability. Similarly, its physical properties and properties allow the production of castings with excellent specific characteristics, in particular heat and heat resistant, wear-resistant, and castings with special physical properties. The disadvantage of gray cast iron is its high brittleness. This feature is due to the production of cast iron with nodular graphite. Another disadvantage is the relatively high dispersion of properties, particularly mechanical ones, even in a stable composition [5].

The study results of the influence of chromium, molybdenum, and aluminum on the structure and individual mechanical properties of Ni-Mn-Cu cast iron in the cast, and heat-treated states are presented. All raw castings had an austenitic matrix with relatively low hardness, making the material suitable for machining. Additions of chromium and molybdenum resulted in a higher tendency to hard spots. However, a small addition of aluminum somewhat limited this trend. Heat treatment, which consists in holding castings at 500 ° C

within 4 hours, led to the partial transformation of austenite into acicular, carbon-rich ferrite, similar to bainitic ferrite. The degree of this transformation depended not only on the value of the nickel equivalent (its lower value led to a higher degree of transformation) but also on the content of Cr and Mo (the degree of transformation increased with an increase in the total concentration of both elements).

Castings with the highest degree of hardness showed the greatest hardness, and the increase in hardness caused by heat treatment was greatest in castings with the highest degree of austenite transformation. Adding Cr and Mo led to a decrease in the thermodynamic stability of the austenite, so this turned out to be a favorable solution. For this reason, castings containing the largest total amount of Cr and Mo with the addition of 0.4% Al (to reduce the tendency to crack) showed the highest tensile strength [6].

In [7], the issues of the durability of thermally stressed castings used in practice are considered. It is necessary to know in detail the value of the thermal stress of cast iron, as well as the conditions of thermal stress (the level of operating temperature or its fluctuations, i.e., thermal conditions) for the correct choice of the chemical composition and structure (macro- and micro) of the material. A successful solution to this problem has now been proposed with the help of a simulation program, including optimization of the design of parts (castings). This requires a comprehensive theoretical analysis of the value of thermal stress, i.e., the influence of various physical parameters on its occurrence, flow, and magnitude.

The solidification of low sulfur (<0.05%) and very low aluminum (<0.005%) cast iron molten and superheated in induction furnaces without acid crucible linings and the effect of overheating on the quality of cast iron with efficient metallurgical processing for use was studied under these conditions [8].

The supercooling during solidification increases with increasing superheat, which is associated with significant changes in the chemical composition; for example, C, Si, Mn, Al, and Zr are involved in the formation of graphite. The concept in this article supports the three-stage model of nucleation of flake graphite [(Mn,X)S type nuclei]. There are three important groups of elements in electric iron [deoxidizer/Mn, S/modifying] and three process steps [overheating/base iron pretreatment/final modification].

Various materials have been used to pre-treat the iron melt to control oxidation levels and/or stimulate graphite nucleation sites, including carbon materials and metallurgical silicon carbide. Particular attention was paid to maintaining Al and Zr recovery in the smelter due to their effect on the cast iron structure. Double treatment with strong oxide-forming elements, such as Al and Zr,

for pretreatment with subsequent modification reduces the parameters of eutectic subcooling. This treatment improved the characteristics of the graphite and prevented the formation of carbides. For foundry applications, it is recommended to use a (Mn,X)S compound that is compatible with the graphite nucleating agent with less eutectic subcooling. Attention is drawn to the provision of the control coefficient (%Mn) × (%S) in the range of 0.03 - 0.06 at an Al and/or Zr content in the modified gray cast iron of 0.005 – 0.010%.

## 2 Characteristic indicators and method of obtaining synthetic cast iron

The theoretical basis of modern metallurgy is physical chemistry and especially its constituent parts - thermodynamics and kinetics of processes. Synthetic cast iron is called cast iron obtained in induction furnaces by remelting chips, steel trimmings, and other low-value wastes with further carburization of the melt and bringing its chemical composition to a predetermined one. Upon receipt of synthetic cast iron (SC) the nomenclature of charge materials and their oxidation affects the overall waste of the metal, as well as the way in which ferroalloys and carburizers are introduced; the heating temperature and metal exposure also play an important role. In the smelting of synthetic cast iron from cast iron shavings, the metal waste is more than 2-2.5 times compared to smelting from steel shavings. With this input of ferroalloys and carburetor into the charge, it is 1.3-1.5 times less than when it is introduced into liquid metal. This is because the chips are always somewhat contaminated; they distinguish between weight and a true metal waste. Based on these data, it is possible to plan and calculate the number of oxides of Fe, Mn, Cr, Si introduced by the charge, and the difference relates to the clogging of the charge, in this case, the true waste of the metal is less by 20-25% [9].

In the smelting of synthetic cast iron from steel shavings, it is from 0.3 to 6.2%, and from cast iron, 5.3-9.0%. Let's compare the mechanical properties of synthetic and cupola cast irons with equal carbon equivalents. We can note the dependence on the initial charge materials, composition, heating temperature, and metal holding. So, in cast irons obtained from steel chips, graphite inclusions are large, isolated, and compact or very long, slightly swirled plates with blunt ends. On the contrary, in cast irons obtained from cast iron shavings, graphite plates are small and medium, strongly swirling, intersecting with each other.

The difference in the amount and shape of graphite at equal carbon equivalents and similar pouring temperatures affects the mechanical properties: for cast irons smelted from steel chips, they are higher than for cast irons from cast iron chips. With an increase in carbon equivalents, the tensile strength, bending strength, and hardness decrease due to the appearance of ferrite in the structure, and the deflection arrow increases.

When cast iron is overheated, the tensile strength does not change. Still, the hardness decreases, and the bending strength and deflection increase, which can be explained by a decrease in non-metallic inclusions and gas contents in the metal, particularly nitrogen [10].

## 3 Preparation of the furnace for the forthcoming melting begins even during the previous melting

To preserve the heat of the furnace lining, and its rational use for heating the charge and reducing the melting period, it is necessary to quickly and efficiently charge the furnace lining and charge the charge. Preparation for melting includes calculation of the charge for a specific steel grade, accurate weighing of the charge components, checking the availability and serviceability of tools and machines for cleaning and filling the furnace lining, the delivery of refractory filling materials, the dosage of the necessary ferroalloys and deoxidizers, the provision of graphite electrodes and nipples for make-up, and many other operations [11].

The preparation of the charge, ferroalloys, filling refractory materials, and the necessary tools are completed no later than 1 hour before the release of the previous heat. Blending melting is the compilation of a list of materials to be filled with an indication of their mass quantities, determined depending on the steel grade being smelted. Blending is calculated by considering the features of the current technological instruction [12].

A prerequisite for compiling a charge is knowledge of the chemical composition of the charge components, planned consumption rates of materials (alloyed waste, ferroalloys, cast iron, scrap), accounting for the waste of elements during melting. The most important operation of preparing the charge for melting is accurately weighing its components [11-13]. On fig. 2. The consumption rate of carburizers (carbon-containing materials) is given in the smelting of synthetic iron in an induction crucible furnace in the form of graphs.

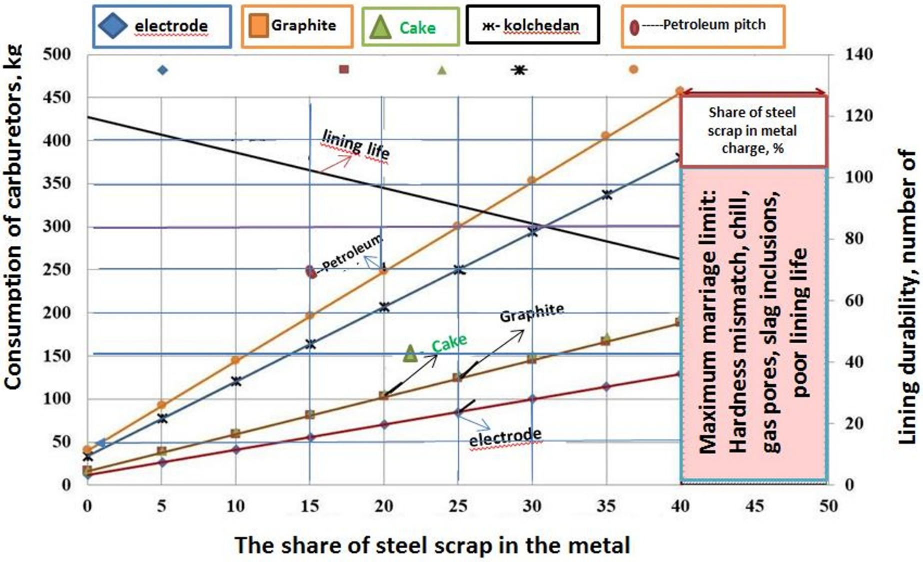

**Fig. 2.** Consumption rate of carburetors (carbonaceous materials) when smelting synthetic iron in induction crucible furnace

The percentage of steel scrap in the production of synthetic iron plays an important role, the share of which should not exceed 40% of the total mass of the metal charge. The consumption of carburizers (kg) as electrode breakage, graphite, coke, pyrites, and petroleum pitch is directly proportional to the share of steel scrap in the metal charge; that is, by varying these components of the metal charge, it is possible to calculate and plan the process of smelting synthetic iron. The resulting material must match the hardness, bleaching, gas pores, slag inclusions, and low lining resistance.

A new concept of technology for melting cast iron in an induction crucible furnace is proposed, which makes it possible to obtain synthetic cast iron using steel scrap as part of the metal charge. The composition of the charge should provide after melting the content of all elements close to that specified in the finished metal. As initial charge materials, foundry and pig irons, return of own production, steel scrap and shavings, carburizers, and ferroalloys are used.

To dilute the metal in terms of phosphorus and sulfur, steel scrap is added to the bath. It is advisable to start the calculation of the metal charge by determining the amount of waste, scrap steel, and carburizers during the melting period, alloying ferroalloys required for additives during the technological period, taking into account obtaining the required composition of liquid iron close to the required one.

**Table 1.** Consumption rate of carburetors with certain proportion of steel scrap in metal charge, kg

| Share of steel scrap in metal charge, % | | | 0 | 5 | 10 |
|---|---|---|---|---|---|
| **Carburizers** | **(C)** | **Assimilation, %** | **Consumption of carburetors, kg** | | |
| Electrode | 98.5 | 90 | 11 | 26 | 41 |
| Electrode Powder | 93 | 90 | 12 | 27 | 43 |
| Graphite coke | 87 | 80 | 14 | 33 | 52 |
| silver graphite | 87 | 75 | 15 | 35 | 55 |
| black graphite | 81 | 75 | 16 | 38 | 59 |

**Continuation of table № 1.**

| Share of steel scrap in metal charge, % | | | 0 | 5 | 10 |
|---|---|---|---|---|---|
| **Carburizers** | **(C)** | **Assimilation, %** | **Consumption of carburetors, kg** | | |
| crucible fight | 91 | 80 | 14 | 32 | 49 |
| Charcoal | 82 | 80 | 15 | 35 | 55 |
| foundry coke | 78 | 70 | 18 | 42 | 66 |
| Metallurgical coke | 78 | 75 | 17 | 39 | 62 |
| Shale coke | 84 | 80 | 15 | 34 | 54 |
| Thermoanthracite | 81 | 75 | 16 | 38 | 59 |
| Kolchedan | 50 | 60 | 33 | 77 | 120 |
| Petroleum pitch | 50 | 50 | 40 | 92 | 144 |

| **Durability of IChT-6 lining with different proportion of steel scrap in metal charge, melts** | | | | | | |
|---|---|---|---|---|---|---|
| Share of steel scrap in metal charge, % | 0 | 5 | 10 | 15 | 20 | 25 |
| Lining durability, heats | 120 | 15 | 110 | 100 | 95 | 90 |

**Continuation of table № 1.**

| Share of steel scrap in metal charge, % | 15 | 20 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|---|
| **Carburizers** | **Consumption of carburetors, kg** | | | | | |
| Electrode | 55 | 70 | 85 | 99 | 114 | 129 |
| Electrode Powder | 59 | 74 | 90 | 105 | 121 | 136 |
| Graphite coke | 70 | 89 | 108 | 126 | 145 | 164 |
| silver graphite | 75 | 95 | 115 | 135 | 155 | 175 |
| black graphite | 81 | 102 | 123 | 145 | 166 | 188 |
| crucible fight | 67 | 85 | 103 | 121 | 139 | 157 |
| Charcoal | 75 | 95 | 114 | 134 | 154 | 174 |
| foundry coke | 90 | 114 | 137 | 161 | 185 | 209 |
| Metallurgical coke | 84 | 106 | 128 | 150 | 173 | 195 |
| Shale coke | 73 | 92 | 112 | 131 | 150 | 170 |
| Thermoanthracite | 81 | 102 | 123 | 145 | 166 | 188 |
| Kolchedan | 163 | 207 | 250 | 293 | 337 | 380 |
| Petroleum pitch | 196 | 248 | 300 | 352 | 404 | 456 |

| **Durability of IChT-6 lining with different proportion of steel scrap in metal charge, melts** | | | | | |
|---|---|---|---|---|---|
| Share of steel scrap in metal charge, % | 30 | 35 | 40 | 45 | 50 |
| Lining durability, heats | 85 | 80 | 75 | 70 | 60 |

The method of smelting synthetic iron in induction crucible furnaces consists of the fact that before melting, it is necessary to calculate the charge, considering the proportion of carburizers, scrap steel, and ferroalloys. The melting of metal begins with the charging of pig iron in the amount of 20-30% of the total capacity of the crucible of the induction furnace. The liquid metal is heated up to 1350°C for 20-30 minutes following the amount of pig iron loaded. Then a carburetor is added, the consumption rate of which, with a different proportion of scrap steel, is determined using the general charge calculation. Table-1 shows the recommended consumption rate of carburetors for different proportions of steel scrap in the metal charge.

To avoid strong oxidation of carbon, a basement of steel scrap is carried out, which keeps the carburetor in the cast iron melt, while the total share of which should not exceed 40% of the total capacity of the crucible. The temperature of the metal melt must be kept within 1390-1410oC. As the steel scrap is deposited, the basement of the return of our own production with ferroalloys is carried out.

The technological process of smelting synthetic iron in an induction crucible furnace with a capacity of 6 tons is that before melting, it is necessary to calculate the charge, considering the proportion of carburizers, scrap steel, and ferroalloys. A large amount of experimental material has been accumulated, which, combined with theoretical developments, makes it possible to organize the production of various cast iron alloys scientifically [14, 15].

Figure 3 shows the process chain for smelting synthetic iron in an induction crucible furnace with a capacity of 6 tons. Let us consider the technology for smelting synthetic iron.

Loading the charge in the ITP up to - 5 min. The charge comprises iron scrap, own return, steel scrap, and coke (charge composition, % C, Si, Mn, P, S, etc.). Before loading the charge, it is necessary to check the condition of the crucible and tap-hole ceramics, the operation of all mechanisms, water-cooling, and alarm systems.

The melting period lasts - 80 minutes (T = 1350˚C); when the iron is smelted in an induction crucible furnace, the proportion of steel scrap should not exceed 40% when comparing cast irons of the same chemical composition. As the charge melts and settles, a part of it ("basement"), which did not fit during filling, is loaded.

Slag removal - 5 min. After the cast iron is melted, the melted skims the slag from the surface of the liquid alloy, and the temperature is determined using a thermocouple. When the temperature reaches 1350 0C, slag is removed, and samples are taken from the furnace for hardness and chemical analysis using a dry spoon and poured into a dry probe (metal composition, % C, Si, Mn, P, S, etc.).

It should be noted that when the iron is smelted in an induction crucible furnace intended for smelting, steel should not exceed 30% of the furnace capacity since, with accelerated melting of the metal, carbon passes from a free to a bound state (i.e., cementite Fe3C and manganese carbides are formed, chromium, etc.), which leads to inhibition of graphitization, which leads to an increase in the mechanical properties of cast iron.

Alloying - 5 min. When iron is smelted in an induction crucible furnace, the overheating temperature of the liquid metal should not exceed 1400 C. An increase in t overheating of liquid iron over the established t leads to the crushing of graphite inclusions and an increase in the amount of bound carbon, which leads to an increase in the mechanical properties of cast iron. When finishing cast iron in an induction crucible furnace, it is necessary to comply with the standards for sulfur and phosphorus. An increase in the phosphorus content contributes to the release of phosphide eutectic in the form of large inclusions or a network along the grain boundaries, which leads to a decrease in the mechanical properties of cast iron (HB metal composition, % C, Si, Mn, P, S, etc.).

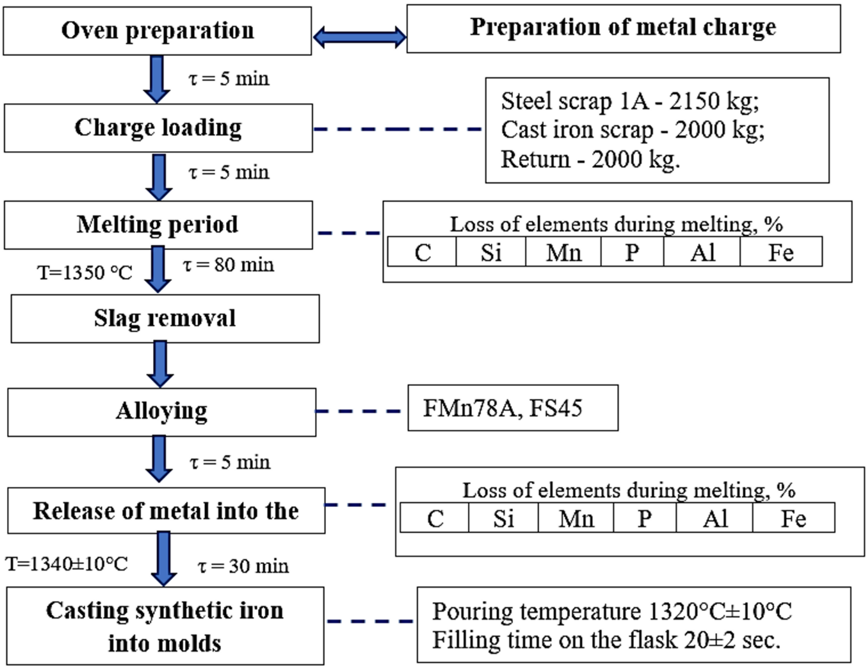

**Fig. 3.** Technological chain of smelting synthetic iron in ITP with capacity of 6 tons

Release of the melt into the ladle - 5 min (T=1340°±10°C). The time for pouring the molds is determined by the OTK controller using a stopwatch, pouring the molds with a full jet, when the metal approaches the profits, reduce the jet so that the metal fills the mold gradually, the edge of the toe must be cleaned of the build-up of metal with a metal crowbar, to prevent slag from entering the mold during pouring.

Start pouring iron at the command of the foreman of the melting section; place the ladle above the gate funnel at the minimum possible height, but not more than 250 mm from the lower edge of the ladle; the axis of the cup opening must coincide with the axis of the mold riser, while filling the molds with melt, the pourer, depending on the filling funnel, increases or decreases the filling speed by adjusting the size of the jet.

Pouring cast iron into molds - When pouring molds, it is prohibited to: interrupt the metal stream; pour metal through the top of the funnel; continue pouring the mold when the metal goes into the socket, under the funnel, and in other cases leading to marriage. A ladle sample should be taken for chemical analysis in the middle of casting. Cast iron pouring temperature 1320±10°C.

Experimental studies of the physical and chemical properties of synthetic cast iron with a different proportion of steel scrap in the metal charge and the specific power consumption for melting were carried out under production conditions in an induction crucible furnace with a capacity of 6 tons. An experimental sample with the required hardness from 230 to 300 HB was selected to evaluate the mechanical properties. The share of steel scrap in the metal charge ranged from 0 to 40%. The experiment's results on the dependence of the technological parameters of synthetic cast iron on the proportion of steel scrap are summarized in Table 2.

**Table 2.** Results of experiment on dependence of technological parameters synthetic cast iron from share of scrap steel

| № | Share of steel scrap, % | Melting time, min | Specific electricity consumption, kW/h | Hardness, HB | Yield of good cast iron, % |
|---|---|---|---|---|---|
| 1 experiment | 0 | 65 | 502 | 210 | 97.5 |
| 2 experiment | 10 | 74 | 510 | 234 | 97.33 |
| 3 experiment | 20 | 81 | 521 | 247 | 97.24 |
| 4 experiment | 30 | 88 | 534 | 279 | 97.15 |
| 5 experiment | 40 | 94 | 542 | 296 | 97.05 |

Using the graphic-analytical method, we analyzed the experiment's results on the dependence of the technological parameters of synthetic cast iron on the proportion of steel scrap. The analysis shows that an increase in the proportion of steel scrap in the composition of the metal charge has a positive effect on the hardness of the experimental sample, with an increase in the percentage of steel scrap from 0 to 40% in the metal charge, the hardness of the experimental sample increases, respectively, from 210 to 298 HB. To achieve the required hardness of the experimental sample, it is necessary to have from 10 to 40% of steel scrap in the composition of the metal charge.

## 4 Conclusion

An effective technology has been developed for producing synthetic cast iron in an induction furnace with a different proportion of steel scrap in the composition of the metal charge. The dependences of the specific power consumption, the hardness of the experimental sample, and the duration of melting on the percentage of steel scrap in the metal charge were established. It was found that with an increase in steel scrap in the metal charge, the melting time and the experimental sample's hardness increase, and the yield of suitable liquid iron decreases. To achieve the required hardness of the experimental sample, it is necessary to have from 10 to 40% of steel scrap in the composition of the metal charge.

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