Development of Supplements Prevention System in Oxygen Converter Process in Order to Increase the Economic Efficiency of Steel Melting

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Abstract. The article analyzes the work of the oxygen-converter shop of PJSC «ArcelorMittal Kryvyi Rih». It is shown that almost half of the total number of blowing supplements (~ 44%) is carried out by temperature. In order to improve the conditions of steel smelting and reduce resource costs, calculations were performed and new technological solutions were found in steel smelting to reduce the number of additives. The study of real smelters demonstrated the need for corrective operations in the smelting of steel using scrap metal of different types. Scrap smelts have a clear relationship between the amount of scrap in the charge and the temperature of the melt in the first dump. The addition of «goat» scrap to the charge has a number of uncontrolled effects on the process due to significant fluctuations in the chemical composition of this type of metal charge. An economic analysis with introducing the developed control mechanism over the course of steel smelting into the software system for conditions PSJC «ArcelorMittal Kryvyi Rih» was performed.

1 Introduction

The modern period of development of the metallurgical industry is characterized by intensification of production, which consists in continuous increase of specific and absolute productivity of metallurgical units, improving the range of manufactured metal products and its quality, which reduces the specific costs of metal, energy and labor costs. As a result, the scale of production of even metal-containing finished products increases in the absence of growth of steelmaking.

Along with the reduction of metal costs, there is a problem associated with production losses. One of the problems is supplements in steel production, which reduce the productivity of the unit and deteriorate the quality of steel. The main cause of blowing supplements is the unstable composition of the metal charge and various fluctuations in the temperature of the loaded charge [1].

The constructive solutions available in real practice to eliminate this problem are not possible for implementation in the conditions of the oxygen-converter shop of ArcelorMittal Kryvyi Rih, which requires a search for new approaches to reduce blowing supplements. In the current conditions, the most optimal direction will be work in the field of software engineering for operational control over the technological process.

The development of information methods of control and management of the technological process has recently opened up new opportunities to improve the processes in metallurgy at all production stages and steel-making production did not stand aside. Researchers obtained mathematical models, discovered new dependencies and refined already known ones [2].

Thus, the purpose of this work is the analysis of melting passports at PJSC "ArcelorMittal Kryvyi Rih" and the search for new technological solutions for steelmaking to reduce the number of additives based on the analysis.

2 Analysis of previous studies

A number of studies indicate that the available methods of carbon control do not provide steel of a given chemical composition from the first felling [2, 3]. A significant contribution to solving this problem was made in the works of V.S. Bogushevsky and co-authors [2-4], who developed a series of mathematical models, including static calculation, dynamic prediction and control mechanisms of melting in a closed mode. In [5], an improved method for calculating the material-thermal balance of oxygen-converter steelmaking was developed, which increases the flexibility of the steelmaking process by using the influence of more correct melting conditions. This will improve the technological process and significantly reduce the number of blowing supplements. However, all currently available developments do not allow to finally solve this problem, therefore, the search for additional mechanisms to control the converter process is an urgent problem.

In recent years, advanced methods have been developed to monitor and control processes in metallurgy. The introduction of powerful computing technology allowed technologists to accumulate and analyze large amounts of data in order to introduce...
advanced automation systems in metallurgy [6], and the development of programming languages allows introducing machine learning elements into metallurgy [7] to refine the developed models directly in the course of technological processes. Due to this, a lot of works have appeared devoted to the introduction into a real production process of models developed to control both the entire technology of steel production, and individual processes. For example, in the literature, there are works on improving the efficiency of using the conversion of CO₂ [8], which leads to an improvement in the energy efficiency of the converter process. Much has been done in the development of models for studying processes at the micro level. Thus, in [9], a model was created for macrosegregation of adhesion under the bloom surface, which takes into account the electromagnetic field, flow, heat and transfer of solutes based on the average volume method to study the effect of electromagnetic stirring in the form of M-EMS, and in the study [10], a model was developed dynamic behavior of the molten bath of the MLA-PBF.

Since 2017, the technical department of the PJSC «ArcelorMittal Kryvyi Rih» has begun a large-scale implementation of the software environment «Steelmaking process in the smart-online» mode [11]. The purpose of this project is to ensure the cyclical operation of the steelmaking process and constant correct informing of the manager and technological personnel involved in the process about the state of production online. The system covers all measuring instruments and sensors, starting from the control of the chemical and physical characteristics of the liquid iron leaving the blast furnaces (fig. 1) and scrap (fig. 2), ending with control over the processes in the continuous casting department.

**Fig. 1.** Characteristics of the liquid iron
Fig. 2. Characteristics of the scrap

3 Materials, methods and results of the study

The use and implementation of this system made it possible to carry out a complete analysis of a number of technological processes, identify the relationship between various factors and identify problem areas in the adopted technology. The most important role for identifying problem points in the steel smelting process is played by the smelting passport and batching model (fig. 3), allowing to control all influences on the molten metal. As part of this work, the authors analyzed an array of more than 500 melting’s passports.
According to the analysis of the oxygen-converter shop of PJSC «ArcelorMittal Kryvyi Rih» almost half of the total number of blowing supplements (~44%) is carried out by temperature. The physical heat of liquid cast iron contributes to the converter bath about 50-54% of the total heat, and an increase in the temperature of the cast iron, respectively, leads to an increase in the temperature of the bath.

Analyzing of the melting’s passports, new relationships were obtained between the indicators of the oxygen-converter process, which are typical for the conditions of the steelmaking shop of PJSC «ArcelorMittal Krivyi Rih».

The dependence of the metal temperature on the first pile on the temperature of cast iron (fig. 4) is represented by the equation:

\[ T_M = -0.0002 \cdot T_{ci.} + 0.5444 \cdot T_{ci.} + 1142.6, \quad r^2 = 0.45, \]

where \( T_M \) is the temperature of the metal on the first dump, °C; \( T_{ci.} \) – temperature of cast iron, which is poured into the converter, °C.

The influence of the amount of cast iron on the temperature of the metal on the first dump (fig. 5) is expressed by the equation:

\[ T_M = 0.0109 \cdot Q^2 - 0.4442 \cdot Q + 1556.3, \quad r^2 = 0.51, \]

where \( Q \) is the amount of cast iron, %.

The dependence of the metal temperature on the manganese content in the cast iron was also revealed – with the increase of the manganese content in the cast iron the metal temperature decreases (fig. 6):

\[ T_M = 7.1733 \cdot [\text{Mn}]_{ci.}^2 - 44.9 \cdot [\text{Mn}]_{ci.} + 1603.8, \quad r^2 = 0.47, \]

where \([\text{Mn}]_{ci.}\) – manganese content in cast iron, %.
As the amount of scrap in the filling decreases, the temperature of the metal on the first dump increases (fig. 7). This is due to the fact that the scrap is a coolant, for its dissolution consumes a certain amount of heat. This dependence is expressed by the equation:

\[ T_m = -0.0559 \cdot P^2 + 1.3936 \cdot P + 1584.2, \quad r^2=0.56, \tag{4} \]

where \( P \) is the content of scrap in the metal charge, %.

Scrap enters to the landfill with a certain degree of slagging, its cooling capacity is greater than that of pure scrap.

All this contributes to the fact that with increasing amount of slag scrap in the filling there is a decrease in metal temperature (fig. 8). This dependence is expressed by the equation:

\[ T_m = 0.006 \cdot P_s^2 - 1.2823 \cdot P_s + 1589.6, \quad r^2=0.41, \tag{5} \]

where \( P_s \) is the content of slag scrap in the metal, %.

The impact of the so-called "goat" scrap has a slightly different character. With an increase in the amount of "goat" scrap loaded, there is an increase in metal temperature (fig. 9).

All these dependences confirm the fact that the "goat" scrap does not actually perform its function as a coolant and leads to an increase in the number of blowing supplements. When sampling unmelted scrap increases heat dissipation due to the cooling effect is 1400-1500 kJ/kg, which is equal to the same value of scrap metal. As a result, technologists are forced to perform blowing supplements operations on temperature with overheating of the melt [12].

\[ T_m = -0.0371 \cdot P_g^2 - 0.619 \cdot P_g + 1574.9, \quad r^2=0.43, \tag{6} \]

where \( P_g \) is the content of «goat» scrap in the metal charge, %.

The use of the obtained mathematical models and their introduction into the smart matrix of the oxygen-converter process (fig. 10) made it possible to significantly improve the efficiency of the shop and improve the technology of steelmaking.
Fig. 10. Smart matrix of the oxygen-converter process

The corrective operations proposed by the authors of the article are based on calculations performed using the material-thermal balance of the oxygen-converter process.

The amount of heat required on average for converter melting is $2.85 \times 10^3$ MJ. Of these, the largest amount of heat (50–54%) gives the physical heat of cast iron, coming from the blast furnace shop. The share of chemical heat accounts for 34–35% of heat input (in the processing of pig iron, the amount of additional heat increases slightly). Blast furnace slag, which enters the converter from the mixer, contributes about 0.6 % of heat [13].

Thus, in the processing of pig iron weighing 10 tons, the same chemical composition as pig iron, is additionally made:

- $[C] = 1.10 - 0.20 = 0.90 \% = 378 \text{ kg}[C]$
- $[Si] = 0.23 - 0.08 = 0.15 \% = 63 \text{ kg}[Si]$
- $[Mn] = 0.46 - 0.46 = 0.00 \% = 0 \text{ kg}[Mn]$
- $[P] = 0.06 - 0.04 = 0.02 \% = 8.4 \text{ kg}[P]$

which gives due to chemical reactions the arrival of heat in the amount 17773 kJ.

That is, for 1 ton of pig iron enters the bath of the converter an additional 17773 kJ. The cooling effect of cast iron is slightly greater than in comparison with
ordinary scrap metal, which is associated with a smaller particle size distribution and, accordingly, a larger area of interaction (table 1).

Table 1. The amount of heat given off by the metal additive

| Name       | Scrap (1 t) | Pig iron (1 t) |
|------------|------------|----------------|
| Heat capacity | 714 kJ     | 2256 kJ        |
| Cooling effect | - 1.45 MJ | - 1.8 MJ       |
| Total       | - 0.736 MJ | 0.456 MJ       |

As can be seen from table 1, the difference in heat input is 1.192 MJ per 1 ton of pig iron. The most effective compensator for excess heat in terms of economic feasibility is limestone (CaCO₃), the cooling effect of which is 12·10⁻³ kJ per 1 ton of cast iron. The main disadvantage of limestone – low reactivity, which does not allow the optimal amount to react in the necessary time interval to ensure high productivity of the steelmaking unit. As a result, the technologist is forced to increase the amount of limestone consumption by 30 - 40 %, which in total is 130-140 kg of CaCO₃ per 1 ton of pig iron.

Along with pig iron, steel scrap is used, the degree of contamination of which ranges from 5 to 40 %, which negatively affects the arrival of heat. The heat capacity of scrap is 714 kJ/t. And from the heat of formation and the content of chemicals in the slag, from the steel scrap can calculate its heat capacity [13]:

FeO  = 23.32 kJ
Fe₂O₃ = 23.86 kJ
CaO  = 168.72 kJ
SiO₂ = 108.51 kJ
MgO  = 49.97 kJ
Al₂O₃ = 88.83 kJ
MnO  = 40.08 kJ
S    = 0.133 kJ
Total: = 503 kJ

Analysis of the difference between the heat capacities of scrap and steel scrap (714 kJ/t and 503 kJ/t, respectively) gives an answer to the questions of technologists of PJSC «ArcelorMittal Kryvyi Rih» relatively large number of «cold» melting trunks that come with steel scrap. Given that the amount of steel scrap averages 10 tons per smelting, it becomes possible to calculate the amount of heat lost due to low heat capacity and a huge cooling effect. Thus, in scrap it varies between 1400-1500 kJ/t, and in steel scrap – 1600-1800 kJ/t. The amount of slag in the steel scrap is 20 %, and the heat input from 1 ton is 671.8 kJ [13]. The heat capacity of steel scrap is less than in scrap by 42.2 kJ/t. Along with this, there is a sharp increase in the cooling effect of scrap (table 2).

Table 2. Cooling effect of scrap and steel scrap

| Name         | Scrap (1 t) | Steel scrap (1 t) |
|--------------|------------|------------------|
| Heat capacity | 714 kJ     | 671.8 kJ         |
| Cooling effect | - 1.45 MJ | - 1.7 MJ         |
| Total        | - 0.736 MJ | - 1.028 MJ       |

As can be seen from table 2, the difference between scrap and steel scrap is 0.292 MJ per 1 ton of scrap metal, which requires additional technological operations for its leveling. The most appropriate in this case is to add ground coke to the purge. Calculations performed according to the existing models of material-heat balance of steel smelting in an oxygen converter [14, 15] show that 104.65 kg of carbon or 120 kg of coke per ton of scrap are needed to generate this amount of heat.

A study of meltings passports shows that the share of “goat” scrap is 8 % of all meltings. In the analysis of these meltings passports the tendency is noticed that at increase in quantity of «goat» scrap the temperature on the first dump increases, which is mainly due to incomplete penetration of scrap. This is confirmed by the data on the average yield of the metal. Thus, in conventional batching the yield of metal is 146.9 tons, and in the processing of «goat» scrap – 141.6 tons.

In the process of dissolving the steel scrap is heat absorption with the same as in scrap, heat dissipation in the range of 1400-1500 kJ/kg, and its heat capacity is lower than that of scrap metal. Therefore, to avoid blowing supplements by temperature, it is necessary to overheat the bath of the converter by 20-30 °C, which affects on the oxidation of the metal and the amount of dissolved nitrogen in the metal.

4 Results, discussion and economic justification

The performed analysis of the oxygen-converter smelts showed that the average duration of one smelting on AMKR is 54 minutes, and the blowing supplements with duration of 4-5 minutes is carried out on each melt (fig. 11).

Experimental smelting operations carried out in the converter shop of PJSC «ArcelorMittal Kryvyi Rih» with using mathematical models developed by the authors, showed the possibility of obtaining the specified physical and chemical properties of the metal at the outlet in 75-85 % of all cases.

An analysis of the shop's operation shows that one converter smelters 3724 tons of steel per day, with the duration of technological operations spent on one melt 54 minutes. If the developed and proposed adjustments are made, the duration of one melt will be reduced to 50 minutes, and the converter productivity will increase to 4032 tons of steel per day. Thus, the daily increase in the volume of steel will be 308 tons. Since not all smelting can be carried out without blowing supplements, and taking their quantity as 50 %, additional steel volume from one converter will be 154 tons. With the average price of 1 ton of steel at $ 225, the cost of additional production will amount to $ 38,500 per converter.
5 Conclusions

The use of modern software solutions for the automation of industrial processes is gradually becoming the most important attribute of large metallurgical enterprises. The results presented in the work clearly demonstrate that traditional steelmaking technologies have huge reserves for improvement.

The use of mathematical models, developed and implemented by the authors in production processes in PJSC «ArcelorMittal Kryvyi Rih» conditions, made it possible to obtain an additional yield of suitable metal worth $38,500 on a daily basis.

Comparing the results of the analysis of smelting passports and the obtained mathematical models through the prism of the possibility of introducing them into a real production process with the results of foreign studies [6-10], we can say that the proposals developed in the article are at a high technological level.

The value of the accuracy of the approximation of the developed computational models shows their sufficient accuracy for use in the modern oxygen-converter process. Despite the fact that the obtained equations, although they reflect the trends known to technologists, their introduction into the converter process control system through the use of modern computer technologies will allow improving and improving these models "underway", thereby increasing the efficiency of the shop with each melting.

Given the constant growth of the meltings pool passport database, the next stage of this work will be the development and implementation of a «smart» control system for the oxygen-converter process, which could take into account the accumulated «experience» to select the most optimal course of steelmaking.

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Fig. 11. Converter control screen
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