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Some aspets in the electric arc steelmaking production

Деякі аспекти у виробництві сталі в електродугових печах

Abstract. *The electric arc furnace (EAF) is the initial aggregate and the key point in many carbon steel and in most stainless-steel melting plants. In the article new solutions in construction, technology, operations and control, used in modern steelmaking plant, will be presented. On literature background the results of author's investigation in electric steelmaking area will be showed. Special attention will be paid on the foaming slag technology used for thermal efficiency increase which means a low cost operation. New elaborated and patented method of stainless-steel slag foaming technology will be described. With slag foaming is connected the optimization procedure concern on minimum the electrical energy consumption and tap-to-tap time. Industrial application in this area will be presented. As a separate chapter the solution in environmental protection during EAF production will be described.*
Key words: *EAF, foaming slag, electrical energy, steelmaking.*

Анотація. *Електродугова піч (ЕДП) є початковим агрегатом та ключовим елементом на багатьох підприємствах з виплавки вуглецевої сталі та на більшості підприємств з виплавки нержавіючої сталі. У статті представлені нові рішення в конструкції, технології, експлуатації та управлінні, що використовуються на сучасному сталеплавильному заводі. На основі літературних джерел показані результати власних досліджень автора в галузі електрометалургії. Особливу увагу приділено технології спінювання шлаку, яка використовується для підвищення теплової ефективності, що означає низьку собівартість роботи. Описано новий розроблений та запатентований метод технології спінювання шлаку при виробництві нержавіючої сталі. Зі спінюванням шлаку пов'язана процедура оптимізації щодо мінімізації споживання електричної енергії та часу плавки. Представлено промислове застосування спінювання шлаку. Окремим розділом описано рішення щодо захисту навколишнього середовища під час виробництва в ЕДП.*
Ключові слова: *ЕДП, спінений шлак, електрична енергія, виробництво сталі.*

1. Introduction

The electric arc furnace (EAF) is used to steel production about one hundred years. Meantime from simply construction and not complicated production technology to present state of art the furnace was continuously developed. Nevertheless the modern furnace is still based on the classical formulation, enough close to the original idea, obviously technologically and economically improved to make the EAF faster and more efficient.

Steel is currently produced using a two-stage technology. During the first stage liquid metal bath is obtained in the steelmaking furnace (the electric arc furnace as well as the oxygen converter). During the second stage the metal bath is subjected to refinement in the process of the off-furnace steel metallurgy (also known as the ladle metallurgy). The aim of the refinement is to obtain a chemical composition and metallurgical quality which are appropriate for the produced grade of steel. The goal is also to obtain the temperature which would enable proper casting.

The electric furnace steelmaking has been increased continuously in recent years, except last year. This trend is friendly for the environment if one considers that the EAF route facilitates the recycling of steel scrap, the conservation of resources, and the reduction of CO_2 emissions from steelmaking. Among the available tools for metal bath creating, the electric arc furnace seems the highest flexibility with respect to the selection of charge materials and their structure. This particular feature of the EAF allows to select the most convenient charge mix which is less dependent on the level of the market price fluctuations. The feasibility of using steel scrap, DRI and hot metal in a range of 0 – 100% has been already confirmed by a large number of existing installations.

The developments in electric steel making show the big steps to reach the today`s high standard. Importance was the competition to the established AC electric arc furnaces with high transformer performance (SUHP furnaces) by the direct current DC arc furnaces. With these furnaces the repercussion in the mains voltage, the electrode consumption and the noise emission was reduced remarkably. The DC electric arc furnace operates with just one graphite electrode in the roof operating as the cathode, and a bottom anode in the bottom.

Process modeling is often used for the observation and control of the EAF process. Online process models allow the calculation of values incapable of measurement like the actual liquid and solid steel and slag mass in the furnace or the permanent monitoring of the actual mean temperature of the liquid steel.

Two particular solutions to modern electric arc furnace steelmaking are presented below.

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2. The foaming slag techology

Since many years the foaming slag practice in the EAF is well established in low alloyed steel production. It improves thermal efficiency of the melting, lowers refractory and electrode consumptions, and provides a stable arcing at lower noise level. Good foaming effect is attainable by suitable slag viscosity strong affected by iron oxide content in the slag as well as permanent iron oxidation and iron oxide reduction by injected oxygen and carbon into the metal bath and slag, respectively. In case of high alloyed steels with high chromium content the preconditions for slag foaming effect are diametrical different. Oxygen injected into the steel produces mainly chromium oxide with totally different properties in comparison with iron oxide, it changes significantly the slag viscosity. The solubility of chromium oxide in the slag is considerable weaker in comparison with that of iron oxide at the same thermal and basicity conditions. Also the reduction of chromium oxide by carbon does not attain such intensity as the reduction of iron oxide. The gas generation is poor. The oxygen/carbon injection technique in the high chromium alloyed steel production is due to the chemical and physical conditions evidently hazardous and difficult in operation. The risk of uncontrolled oxidation of chromium is pronounced, resulting in high chromium losses and poor foaming.

The novel technology distinguishes principal from the conventional one, which uses injection of oxygen and carbon via manipulator lances. The new technique bases on the reduction of iron and chromium oxide by carbon as well as on the thermal dissociation of lime stone contained in a small dimensioned briquette. Specific density of the briquettes is assorted to have value between slag and metal. Its introduction into the melt causes placing exactly on the slag and metal boundary - optimal place for the requested gas generated reaction.

2.1. Idea of slag foaming formation

Two factors define the foamy slag formation: the foaming material with the corresponding reacting components, which produce gaseous products, and the slag viscosity dependent on the chemistry and temperature. A liquid slag is for the foam formation a prerequisite.

The principal reaction that creates gas bubbles in the slag is the reduction of iron and chromium oxides are given by the following stoichiometry:

$$(FeO) + C_{particle-or-dissolved} = [Fe] + \{CO\} \quad (1)$$

$$(Cr_2O_3) + 3C_{particle-or-dissolved} = 2[Cr] + 3\{CO\} \quad (2)$$

The reaction (1) in carbon steelmaking is the principle and iron oxide is the major component in the slag. When the slag viscosity is suitable for sustaining foam, then the simple carbon injection into the slag causes the foaming effect. Other situation is in case of stainless steel slag. The major components are CaO, SiO_2 and Cr_2O_3. The SiO_2 is a fluxing component, while the Cr_2O_3 stiffens the slag. Due to the higher chromium affinity to oxygen the Cr_2O_3 generation takes place preferentially in comparison with FeO. Therefore it is important to control the chromium oxide content and the slag basicity, responsible for the viscosity, which constrains gas bubbles to temporary detainment in the slag layer.

The bubble forming phenomenon is a process of formation new surface area by the mechanical force resolved by reaction gas. In the presented technology this gas is effective for the reduction reaction of metal oxides by carbon taking place in a briquette or pellet introduced into the metal bath. Buoyancy forces of bubbles crack the slag surface saturating temporarily the top layer to create the foam. With a sustained gas flow coming from the reacting briquettes the population of the bubble aggregation as foam continues to grow. As a consequence of it, the height of the foam layer increases. Importance for such mechanism is the optimal placing of the briquettes to get the maximum foaming effectiveness. It is the boundary between the slag layer and liquid metal. With the control of the briquette density, corresponding to the range between that of slag and metal (3-7 t/m^3) such placing is always reachable. The foam height increases with the increase of the gas flow rate; it is directly proportional to the foaming material rate.

Fig. 1 illustrates the principle of the slag foaming.

Theoretical considerations and laboratory tests

The aim of this laboratory experiment was to establish adequate forms and chemical compositions of the materials for effective foaming of high chromium oxide slag. The materials were supposed to contain iron oxide scales, carbon carriers, and high-carbon ferrochromium as weighting agent as well as possibly calcium carbonate as additional producer of gas for foaming process. As to the form of the foaming materials either briquettes or pellets of different sizes were considered. Furthermore, the research study was carried out by making laboratory heats, sampling metal and slag phases for chemical analysis in order to optimize the foam ability.

In the first stage of the work, the most promising materials for foaming were selected based on theoretical considerations. A model for computation of the specific densities of the foaming mixtures was applied.

In the second stage of the work, the foaming mixtures were prepared in forms of briquettes and pellets of different sizes. A number of 40 heats were performed in a laboratory arc furnace to investigate the impact of various parameters on the height and stability of the generated foams [1].

In the third stage, the experimentally obtained results were analysed and the final conclusions and technological recommendations as to the optimal conditions for the slag foaming were established.

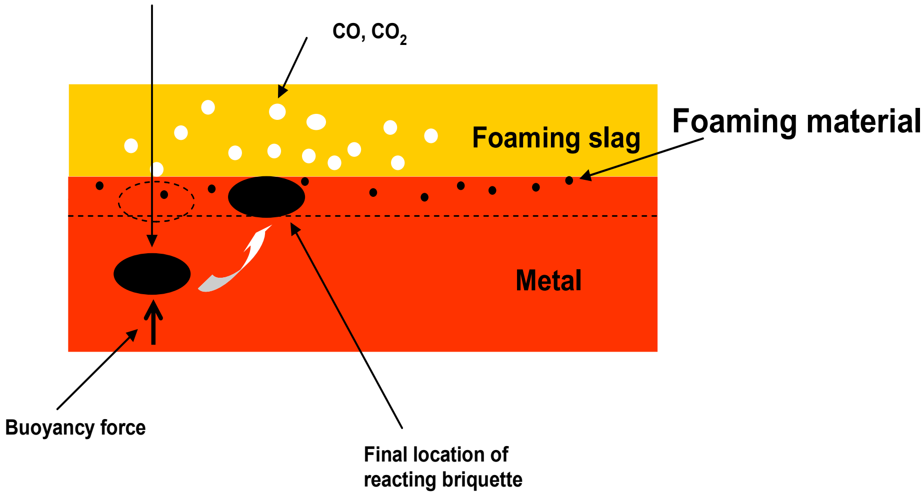

Figure 1. Principle of foaming slag formation by briquette.

Results indicate that the highest foamability was obtained for the pellets of a 8-10 mm diameter, while the lowest for those of a 2-5 mm diameter. The effect is due to the fact that small pellets do not sink trough the slag layer down but float up to the slag surface. The phenomenon is caused by the interfacial tension forces at the pellet/liquid slag boundary. While floating on the slag surface, the bubbles formed in the pellets do not go into the slag layer but go into the ambient atmosphere. For pellets, the foaming time was lower than this for briquettes. It can be explained by the kind of their structure. Briquettes which are compressed materials have lower porosity. Decreased contact surface with liquid slag causes slower heat transfer, slower reduction of the iron oxides in the briquettes and in consequence lower gas rate. Only briquettes were selected for industrial examination.

Industrial tests

On the base of the above described laboratory test the industrial test of foamy slag at high Cr-oxide in an EAF was carried out to prove its industrial functionality as well as viability. The EAF-AC with the capacity between 25-35t and transformer of 32 MVA is designed for pre-metal production of austenitic and ferritic steel grades in common operation with the down stream operating 80t AOD-L and MRP-L converters.

The test being integrated into the current production consisted of 45 austenitic and 15 ferritic heats. The test procedure distinguishes from the normal operation, where oxygen is blown during the whole super heating period. The reason of such procedure was to separate the oxygen effect on the carbon and metal oxidation, additional generation of CO bubbles, as well as impact effect of the gas stream. Several heats were tested under normal operational conditions.

As the test results show, the foaming of a Cr_2O_3 rich EAF slag is a difficult but under controlled slag conditions possible task. Results of this industrial test confirm the correct recipe of the foaming material and the optimal reacting place of the briquettes. Further experiences of the test show also dependences between the initial slag amount and its foamability. Intensive gas development in combination with the slag mass and the desired low viscosity allows slag generations with sufficient height for complete cover of the electric arcs. The optimal initial slag amount fluctuates in the range 68-72 kg/t_{steel}. Fig. 2 illustrates areas of slag composition after briquette additions. It can be seen, that the most slags were good reduced. The average residual Cr_2O_3 in the slag was indicated by 4,2%. Also the basicity in the range 1,3-1,35 was established as optimal. This part of the slag system must be considered to be the optimum area. The viscosity is in this part low, however, partly undissolved lime and higher Cr_2O_3 content increases the viscosity. Fig.3 illustrates a typical slag height development of a AISI 304 heat. The slag heights were measured with a reference to the electrode diameter.

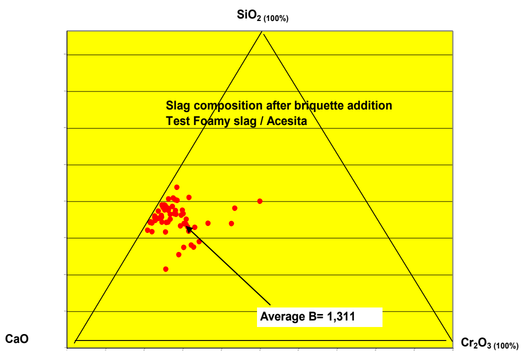

Figure 2. Standardized slag diagram.

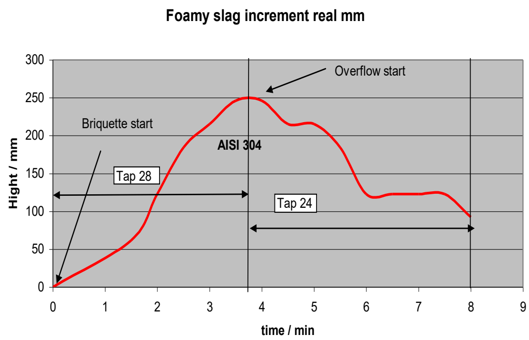

Figure 3. Slag height course.

As the curve shows, after approx. 2 minutes the slag reached the adequate height suitable for the electric arc cover. During the next 4 minutes this level was established, leaving the required range after 4 – 5 minutes. It should be mentioned, that since the 3.5 minutes an overflow of the slag through the furnace door was observed. The slag mass was relating to this continuous reduction until a stable level was reached. It was observed in other tests with oxygen blowing, that the oxygen stream support in the receipt of the foaming layer. In view on the electrode consumption the foamy slag has an undisputed significance.

All tests demonstrate that the new foaming slag technology for stainless steelmaking in EAF which is carried out by foaming materials containing scale, carbon and ballast materials, introduced into the furnace in briquettes form with a special defined density and in combination with a controlled slag viscosity implicates sufficient foaming quality and its height. The slag height is controllable by intensity and duration of additions.

3. The optimisation of the electric energy consumption in the EAF

The aim of steel production in the arc furnace is obtaining the liquid metal bath from the scrap metal as quickly as possible and using as low costs as possible. The structure and the construction of the furnace is subordinate to the aim. So it is the technological method of running the process. The technology of the process encompasses proper preparation and loading of the charge materials (scrap, slag forming materials, carburizing materials) as well as their melting by means of electric energy transformed into heat in the electric arc. The optimal control of the work of an arc furnace with the alternating current is a complex process due to the quantity and variety of the working parameters. Many physical phenomena as well as chemical reactions take place during the melting process. Their precise mathematical description does not seem possible. At the same time the competition at the steel market requires the furnace to work economically which is tantamount to a decrease in production costs. It is impossible to optimize the furnace work in a way that would decrease the costs and produce high quality steel in a universal way at the same time. Different producers apply different methods of controlling the production costs.

Therefore, an attempt has been made to optimize the demand for electric energy used in the production process in the arc furnace. The used energy is one of the most important components of the production costs. If one plans such parametres of the furnace that would optimize the use of energy, the costs will go down.

3.1. The concept of the model

Many physical and chemical phenomena, which take place during the steel melting process in the electric arc furnace, can be presented by means of the physical and chemical models decribing these phenomena. One of such phenomena is calculating the demand for electric energy. Preparing a model of electric energy demand will enable the optimisation of the electric energy consumption. So far many models used in industrial practice have been described in literature [2-5]. The most often used methods included the method of selecting the equation's form and determining the facors. The use of modelling based on the physical chemistry of the process is a difficult task on account of a large amount of simultaneous physical and chemical phenomena requiring a complex mathematical description. Therefore, an attempt was made to use a method based on the calculus of probability. The genetic algorithm method was used in order to identify the available statistical equations describing the use of electric energy in the arc furnace (Figure 4).

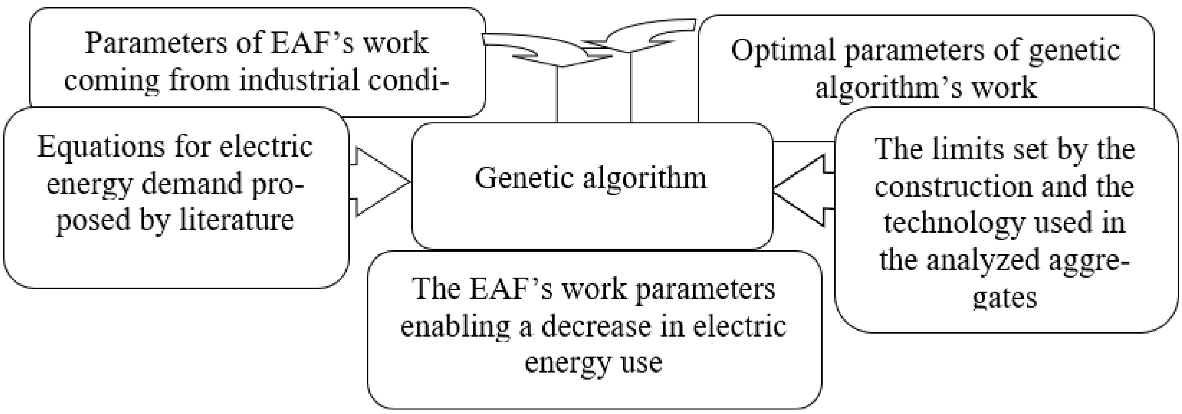

Figure 4: A schematic diagram of the proposed model

3.2. The obtained results

Elaborated software was used to calculate such factors of the melting process that would ensure minimal demand for the electric energy. The obtained results were compared with minimal, maximal and medium values from the actual real melts.

The developed software AGEAF was used to calculate the optimal demand for electric energy in the steelmaking process in the electric arc furnace. The real parameters describing the steelmaking process with values ranging from the minimal to maximal values were used as the entry data. The values of the parameters were established according to the AGEAF algorithm in order to obtain minimal demand for electric energy. The energy was calculated by mean of different equations, detailed described in literature [6]. The obtained results, as an example, and average values for the real melting processes are shown in Table 1.

Table 1. The average values from real melts and the obtained factor values which enabled minimal energy consumption and which were calculated the AGEAF software use.

Factor's name	Average values of real melts	Predicted values			
		Equation *a*	Equation *b*	Equation c	Equation *d*
Calculated value of the electric energy demand, kWh/Mg	396	294	273	293	285
Weight of metallic charge, Mg metalicznego, Mg	157	151	145	153	159
Weight of melted metal, Mg	140	145	148	149	152
Weight of remaining metal, Mg	10	6.2	4.6	7.6	3.0
Slag weight, Mg	10	10	10	10	10
Oxygen used for the process, m^3/Mg $^3/Mg$	33	33,5	35	32	34
Gas used for the process, m^3/Mg	3.4	2.8	2.15	3.5	4.9
Temperature of the metal bath before tapping, ^oC	1609	1609	1609	1609	1609
Tap to tap time, min	52	58	53	55	61
Time of energy consumption by the furnace, min	40	35	40	44	42

* *- detailed description of equations (a) ÷ (d) is included in literature [6]*

The minimal demand for electric energy calculated on the basis of equations is in each case smaller than that for the real melting processes. Consequently, it is possible to select such values of particular factors that would lower the demand for electric energy. The analysis of particular values of different factors led to the conclusion that equation (*b*) best reflects the real working conditions of the investigated arc furnace. In order to optimize the demand for energy, it is advised to use the above mentioned equation. As can be seen from the data in Table 2, the calculated values of particular factors are different from the average values from real melting processes. The smallest difference that can be noticed is that in the time from one melt to another and the biggest difference is that in the melted metal weight. Such results show that the time from one melt to another has the biggest influence on the energy demand. The factor showing the biggest difference from the average real value has the least significance when it comes to energy demand. Similar relations were obtained as far as other analyzed equations are concerned.

The analysis of the results shows that the quality of the database used for optimizing the energy demand is not the best. It can be said that the minimal and maximal values used in optimizing the energy demand were coincidental to a large extent. That is why theoretical minimal and maximal values of particular factors were assumed. They were prepared on the basis of the furnace's construction parameters and technological data and are shown in Table 2.

Table 2. Theoretical parameters for the optimization process in AGEAF software for the furnace.

Factor's name	Values	
	Minimal	Maximal
Weight of the metallic charge, Mg	140	165
Weight of melted metal, Mg	120	162
Weight of remaining metal, Mg	0	10
Slag weight, Mg	8	12
Oxygen used for the process, m^3/Mg	0	50
Gas used for the process, m^3/Mg	0	10
Temperature of the metal bath before tapping, ^oC	1590	1610
Tap to tap time, min	45	55
Time of energy consumption by the furnace, min	35	45
DRI weight	0	5
HBI weight	0	5

AGEAF software was again used to calculate the electric energy demand on the basis of minimal and maximal values from Table 2. The results are presented in Table 3. The results show that the calculated value of optimal, i.e. minimal, demand for energy assessed on the basis of equations (*a*) ÷ (*d*) differs depending on the equation. The smallest value was obtained in the case of equations (*a*) and (*d*). Higher values were obtained in the case of equations (*b*) and (*c*). It means that for such working conditions it is good to use equations (*a*) and (*d*).

Table 3. The factor values which enabled minimal energy consumption and which were calculated he AGEAF software use.

Factor's name	Predicted values			
	Equation *a*	Equation *b*	Equation *c*	Equation *d*
calculated value of electric energy demand, kWh/Mg	297	349	350	298
Weight of the metallic charge, Mg	144	151	159	150
Weight of melted metal, Mg	141	146	147	142
Weight of remaining metal, Mg	8	4.9	9.0	7.7
Slag weight, Mg	10	10	10	10
Oxygen used for the process, m^3/Mg	42,36	32	32,9	40
Gas used for the process, m^3/Mg	3.8	2.7	8.2	7.3
Temperature of the metal bath before tapping, °C	1600	1600	1600	1600
Tap to tap time, min	52,9	50	52	46,5
Time of energy consumption by the furnace, min	38	37,6	38	38
DRI weight	–	4,47	–	2,65
HBI weight	–	1	–	2

* *- detailed description of equations (a) ÷ (d) is included in literature [6]*

The values of the factors which cause the optimal energy consumption show that it is recommended to work on the melting technology. It is recommended to develop such technologies that would use those factors that make the energy demand optimal.

4. Conclusions

Steel is sometimes produced using a two-stage technology. During the first stage liquid metal bath is obtained in the steelmaking furnace but during the second stage the metal bath is subjected to refinement in the process of the ladle metallurgy. Among the available tools for metal bath creating, the electric arc furnace seems the highest flexibility with respect to the selection of charge materials and their structure. This particular feature of the EAF allows to select the most convenient charge mix. Process modeling is often used for the observation and control of the EAF process. Online process models allow the calculation of values incapable of measurement like the actual liquid and solid steel and slag mass in the furnace or the permanent monitoring of the actual mean temperature of the liquid steel.

Two particular solutions to modern electric arc furnace steelmaking are presented in the article:

the foaming slag technology used in case of high alloyed steels with high chromium content and

the developed software used to calculate the optimal demand for electric energy in the steelmaking process in the electric arc furnace.

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