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TITLE OF PhD THESIS

IMPROVEMENT OF THE SECONDARY COOLING PROCESS OF CONTINUOUSLY CAST STEEL

Ph Thesis – Abstract

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author: Eng. GHEORGHIU CSABA ATTILA

Scientific coordinator: Prof. Dr. Eng. HEPUŢ TEODOR

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CHAPTER 1
SCHEDULE OF EXPERIMENTS AND RESEARCH

The researches carried out and presented within the doctoral thesis aimed to improve the quality of the continuous cast semi-finished products, acting on the main parameters of continuous casting.

The research strategy applied for the elaboration of the PhD thesis consisted of the following stages:

- Study of the literature, processing of information and its correlation with the information obtained from the steel-making and casting practice;
- Research on using the FUZZY systems in industry;
- Industrial research and experimentation carried out over a technological flow consisting of steel processing in ladle and continuous casting;
- Final conclusions, original contributions and further developments.

PART I
STUDY OF THE LITERATURE ON STEEL-MAKING AND CONTINUOUS CASTING

CHAPTER 2
STUDY OF THE LITERATURE REGARDING STEEL-MAKING IN ELECTRIC ARC FURNACES AND THE CONTINUOUS CASTING OF STEEL

Currently worldwide, in the steel industry, the thermal facilities used for steel-making are the oxygen converters and electric arc furnaces. In Romania, the economic restructuring after 1989 occurred also in the steel industry, in 1999 being decommissioned the last Siemens-Martin steelworks (OSM II, Hunedoara), so that in our country the steel is currently made in oxygen converters and electric arc furnaces, all steelworks being equipped with continuous casting facilities.

We present in this paper certain technological parameters related to steel-making in EBT-type electric arc furnaces (Eccentric Bottom Tapping) whose capacity is 100 tons, processing in LF (Ladle-Furnace) and VD (vacuum degassing), and continuous cast of semi-finished products with circular section using a casting machine with 5 strands.

After processing in LF and sometimes in VD (if the production technology includes this operation), the steel is continuously and sequentially cast in a casting machine with 5 strands [1-3].

This wide spread of sequential casting is due to the important advantages of this process, as follows:

- Productivity and yield increase as a result of reduced idle times between the heats;
- Metal consumption reduction (or metal yield increase) thanks to the reduction of scrap material from heats and cut ends;
- A more favourable thermal balance of the machine and lower maintenance and operation costs (especially for labour and intermediate rollers).

We note, however, that the sequential casting over a longer period also requires a number of conditions, especially technological, of which the most important are:

- Large orders for the same steel grade and size of the semi-finished product;
- Perfect synchronization between the furnace cycles and continuous casting cycles;
- Correctness and consistency of the chemical composition and casting temperature of the steel, so that it can always be directed to the continuous casting machine, where the heats can be mixed;
- Correct operation of the continuous casting machine to minimize the idle stoppages;
- High quality of the moulds, enabling a prolonged casting and, therefore, a constant heat transmission and preservation of the initial shape.

The following conclusions are drawn from this study:

- At present, most of the steelworks are equipped with high-power EBT-type electric arc furnaces and continuous casting machines;
- The heat duration at such furnaces ranges from 45 to 75 minutes (very close to that of oxygen converters);
- The productivity averages around 100 tons/h;
- It is stipulated in the production flow the processing of steel by the so-called *ladle metallurgy*, typically in LF-type installations, often placed in the same flow with the vacuum installations;
- The processing time in such installations ranges from 42 to 80 minutes, being influenced by the casting sequence structure;
- The tendency is to increase the amount of steel cast in the same sequence (i.e. the number of filled ladles);
- The modern casting facilities ensure the casting of a wide range of semi-finished products of different sections, i.e. polygonal, circular and flat products;
- The current trend is to cast semi-finished products whose section is as close as possible to the final one.

CHAPTER 3
FUZZY SYSTEMS IN THE CONTINUOUS CASTING PROCESS

In the case of Fuzzy regulation, the conventional control algorithms are replaced by a set of linguistic rules, i.e. "**If**" *(the premise)* and "**then**" *(the conclusion)*. Thus, a heuristic algorithm is obtained and therefore the operator's experience in the process management can be taken into account. In these conditions, the Fuzzy logic is well suited to the process management.

The Fuzzy logic controller, unlike a classic controller, does not treat the information through a well-defined mathematical relation (regulation algorithm), but uses multi-rule inferences based on linguistic variables. These inferences are handled by Fuzzy logic operators.

The Fuzzy logic has been introduced to mathematically treat the vague information. The mathematical representation of vague information is based on the introduction of the *membership function* as a measure of the belonging of an element to a set or to a linguistic value. The *linguistic modelling* consists in associating a physical parameter of a linguistic variable with several linguistic values, on the basis of which various membership functions can be associated.

For describing a process, it can be decomposed into several subprocesses, and so it can become very complex. The description of a process can be done in a simple manner, as follows:

If the condition 1, then the operation 1, or
If the condition 2, then the operation 2, or
If the condition n, then the operation n

The various conditions generally consist of several linguistic variables linked to each other by the operators *AND* and *OR*, respectively [4-8].

Applying Fuzzy logic in tuning

The Fuzzy tuning is a simplified version of the Fuzzy logic, because in the Fuzzy tuning it is used a single inference method, which is a combination of exact input values and rules *"if - then"*. These rules are represented by a binary Fuzzy relation.

From the study on Fuzzy systems in the continuous casting process, briefly presented in this chapter, the following conclusions can be drawn:

- The Fuzzy logic controller, unlike a classic controller, does not treat the information through a well-defined mathematical relation (regulation algorithm), but uses multi-rule inferences based on linguistic variables;
- The first applications of Fuzzy logic in regulatory systems appeared in 1975, and since 1985 the Japanese have used it in industrial processes to solve the control issues;
- In Europe, the research on the application of Fuzzy logic in regulation began later; for example, in Germany the year of starting a systematic research is considered to be 1991;
- The Fuzzy tuning systems can be considered recent and, as a result of more research, new technical information can be provided in this field.

PART II
RESEARCH AND EXPERIMENTS ON THE MANAGEMENT OF THE CONTINUOUS CASTING PROCESS USING FUZZY SYSTEMS

CHAPTER 4
RESEARCH ON IMPROVING THE SURFACE QUALITY OF THE CONTINUOUS CAST SEMI-FINISHED PRODUCTS

In this chapter, we considered the investigation of some processes occurring inside the mould, at the continuous casting of steel, leading to a sufficiently thickness of the solidification crust to do not generate surface defects, on the one hand, and on the other hand enabling a good lubrication, so leading to a non-cracked surface of the semi-finished products. In this respect, certain correlations have been established between the viscosity of the lubrication slag and its chemical properties, as well as in case of interphase tensions. The data were processed in EXCEL and MATLAB calculus software, the results being presented in analytical and graphic form and analysed from the technological point of view.

The multiple correlation enables the selection of optimal values for temperature, MgO, CaO/SiO_2 and Al_2O_3, which results in obtaining a viscosity within a specific range, depending also on the cast steel (casting temperature, size of the semi-finished product, destination, etc.); it is advisable to range between 0.4 and 1.4 Ns/m^2.

Variable variation limits: dependent / independent: $CaO/SiO_2 = 0.7 - 1.14$; $(Al_2O_3+MgO) = 5.85 - 14.9\%$; $T = 1200 - 1500^oC$; Viscosity $\eta = 0.08 - 5.14\ Ns/m^2$;
Average values / deviations of variables: $CaO/SiO_2 = 0.88221 / 0.10503$; $(Al_2O_3+MgO) = 8.9374 / 2.1778$; $T = 1332.8 / 99.163$; $\eta = 0.8469 / 0.84795$.

Equation of the regression hypersurface:

$$\eta = -3.8075 \cdot CaO/SiO_2^2 + -0.0043 \cdot (Al_2O_3 + MgO)^2 + 1.9617e-005 \cdot T^2 + -0.6181 \cdot CaO/SiO_2 \cdot (Al_2O_3 + MgO) + -0.0011 \cdot (Al_2O_3 + MgO) \cdot$$
$$\cdot T + 0.010126 \cdot T \cdot CaO/SiO_2 + -2.7738 \cdot CaO/SiO_2 + 2.2249 \cdot (Al_2O_3 + MgO) + -0.057106 \cdot T + 33.962$$

The correlation coefficient: $rf = 0.9547$; Deviation from the regression surface: $sf = 0.2524$;

The coordinates of the saddle point are: $CaO/SiO_2 = 0.92793$; $(Al_2O_3+MgO) = 7.4678\%$; $T = 1427.6228^oC$; $\eta = 0.21964$;

Since this hypersurface cannot be represented in the 4-dimensional space, the successive replacement of an independent variable with its average value has been used. These surfaces, which belong to the 3-dimensional space, can be represented and interpreted by the technologists.

On the basis of the research carried out (i.e. the obtained results), we can conclude as follows:

- Between the cooling parameters in the secondary area of the continuous casting machine and the continuous casting speed we can establish representative technological correlations, expressed analytically and graphically;
- On the basis of the graphical representations, it is possible to select the prescribed casting speed according to the steel casting temperature and the flow rate of the casting water;
- The results can be used in practice to cast semi-finished products ∅180 mm.

CHAPTER 5
FUZZY SYSTEM FOR CONTROLLING THE WATER FLOW FOR SECONDARY COOLING OF THE STEEL

This chapter proposes a Fuzzy solution which, fitted to the existing structure of the continuous casting system, eliminates the cracks occurring in the secondary cooling zone by generating the necessary adjustments to change the set water flow rate and casting speed.

The existing crack removal systems cannot remove the cracks when they are detected in the secondary steel cooling zone, but, using the proposed predictive principle, this disadvantage is practically eliminated. The rule base is specifically designed for this purpose and includes the steps to be taken to mitigate the risk of a crack when it has not yet occurred.

At present, the continuous casting provides the largest share of semi-finished products for the metallurgical industry. The process is very complex, with high productivity, but, due to technological problems, it can generate quality defects caused by crust cracking. These defects lead to a lower quality of the semi-finished products and financial losses. The continuous casting field has been developed and strengthened as an important research direction, concentrating the collective research efforts of many academic and metallurgical specialists [9-14].

The introduction of such a smart system is a relatively new approach in the field. The Fuzzy system can be adapted to all types of continuous casting machines because it does not require major hardware changes and can be applied to any continuous casting machine.

Because the prerequisites and rules are changing according to the zone where the billet is located, it was necessary to design different Fuzzy systems for each individual cooling zone.

The input data processing generates the corrections necessary to modify the required values of the casting speed and the secondary cooling water flow, in order to eliminate any cracks from the billet.

It is for the first time at national and global level when it was ordered to change the six parameters (v_1, v_2, v_3, q_1, q_2, q_3, the casting speed and the cooling water flow rate for each cooling zone separately) for removing the cracks from the continuous cast billet. The rule bases are designed so that the first parameter that changes is the flow rate of the cooling water, followed by the casting speed. This principle has been used to maintain the casting machine productivity as far as possible (the decrease in casting speed leads to lower productivity).

IFS design

The actual design of IFS was done in Matlab software using the Fuzzy logic toolbox. Basically, there are three IFSs, one IFS for each zone of the secondary cooling area, called IFS ZONE 1, IFS ZONE 2 and IFS ZONE 3, the input parameters being the casting speed (**v**), the water flow rate (**q**), and the steel temperature (**T**).

The three systems have 3 outputs, i.e. the cooling water flow rate correction, the casting speed correction and the technological risk.

For the qualitative analysis of IFS operation, it is proposed to simulate it using the Matlab-Simulink environment. The temperature reading is simulated with the data obtained from the process using a numeric data string. To start the simulation, we need to enter the values of casting speed and water flow rate, and the software will correct these values using a loop through which the obtained correction is changing the input data. The running time of the simulation is 1000 seconds, each calculation loop lasting 3.2 seconds.

Conclusions

Based on the research conducted and presented in this chapter, the following issues can be concluded:

- It was proposed an original Fuzzy solution fitted to the existing structure of the continuous casting control system that eliminates the cracks from the cast material in the secondary cooling zone;
- It was designed the scheme of a Fuzzy decision system which, by analysing certain parameter values taken from the process, is changing the cooling water flow rate and casting speed;
- In the national and global literature there is no information about any intelligent correction of the water flow rate during the secondary cooling of steel, with a real-time adjustment per cooling zones;
- The rule bases were made using the experience of human operators and the information collected directly from the process at the continuous casting machine that belongs to ArcelorMittal Hunedoara S.A.;
- The verification and confirmation of the rule bases and the designed IFS was made by simulation using the Simulink software;
- From the analysis of the simulation results it is noted that regardless of the values generated at input, the IFS is making the necessary corrections of the casting speed and the cooling water flow, which confirms the validity of the system;
- From the qualitative point of view, the use of Fuzzy decision-making system is an efficient, practical and easy to implement method for analysing complex and non-linear phenomena.

CHAPTER 6
WATER FLOW RATE CONTROL BY MEANS OF A PLC PLACED AT THE SECONDARY COOLING ZONE

Introduction

In this chapter we propose a solution for controlling and optimizing the cooling water flow rate in the secondary zone of the continuous casting using a PLC (programmable logic controller) SIEMENS S7 300. Starting from the real structure of the control system for a modern continuous casting machine, an effective solution is proposed here, which enables real-time modification of the water flow rate distribution on the three secondary cooling zones. The proposed system was tested and validated following the experimental determinations carried out on a laboratory stand, as well as on the existing continuous casting machine at ArcelorMittal Hunedoara S.A [15-17].

The PLC stand

In order to achieve the goal proposed in this chapter, we realised an experimental stand dedicated to the control and optimization of the water flow rate in the secondary cooling zone of the continuous casting of steel.

The realisation of the experimental stand included two stages, as follows:

- Designing and embodiment of the stand (the hardware stage);
- PLC programming (the software stage).

The control and optimization of the water flow rate in the secondary cooling zone of the continuous casting are important for the proper development of the technological process in order to obtain high quality semi-finished products.

Currently, at ArcelorMittal Hunedoara S.A., the cooling water flow rate is regulated by a human operator, which takes information about the steel temperature in the secondary cooling zone from another operator who measures this parameter at certain time intervals, by means of a temperature probe. The operator sitting in the control room has, according to the type of product, an Excel sheet, which contains the following data:

- The casting parameters for the product type;
- Diagram of casting speeds versus temperature;
- Formula for calculating the liquidus temperature.

The operator sitting in the control room identifies the temperature range for the 270x240 mm profile from the "casting speed diagram" (in our case, 26-35°C) and enters the speed value of 0.75 m/min in the field "set speed". According to this value of the speed, the software commands the opening or closing of the cooling system valve, in order to ensure the total flow rate of the cooling water, but also the cooling water distribution over the three zones.

After some time (7-10 minutes), the process is resumed and the data are re-entered. This existing solution has the following disadvantages:

- Subjective errors induced by the human factor (the operator reading the temperature);
- Long time interval between consecutive readings;
- The delay in opening the valve ("delay" means the difference between the moment of reading the temperature and the moment of controlled opening of the valve).

In order to carry out experimental determinations, a measuring program was carried out, which aimed to determine the temperature values in order to correlate the temperature with the casting parameters. This program includes the following stages:

- Preparation of measurements, selection of devices, temperature sensors, materials and accessories necessary to carry out the experimental measurements;
- Establishment of the real conditions for carrying out the measurements;

- Installation and calibration of the temperature sensors;
- Carrying out experimental measurements and processing of the obtained results.

In the first stage of preparing the measurements, selection of devices and temperature sensors, in the current practice as well as in the literature, several practical methods for measuring the temperature have been identified:

- Direct measurement of the steel temperature in the tundish using a thermocouple lance (the current situation);
- Direct measurement of the steel temperature in the tundish using infrared cameras;
- Direct measurement of the steel temperature in the tundish using a ceramic insulated thermocouple (durability: 24 heats).

These methods have a number of advantages and disadvantages; the first method has low costs but, as disadvantages, it does not measure continuously the steel temperature in the tundish (time interval: about 10 minutes), inducing subjective errors due to the human factor (the operator) [17-19].

The second method overrides the disadvantages of the first method, but it has been demonstrated in practice that, because of thermal insulation powders, the reading using these infrared cameras is erroneous (values considerably lower than the real ones).

The last method of direct measurement taken into account has the advantage of continuous measurement of steel temperature in the tundish, eliminates the human factor, but has relatively high costs.

Due to the proposed goal, the latter method has been chosen, and the costs can be amortized by optimising the cooling in the secondary zone and, implicitly, by increasing the steel billet quality.

After installing the thermocouple and the PLC-compatible signal acquisition, experiments were made for three different sizes (Ø180 mm, Ø200 mm, and Ø250 mm), but the same steel grade (20Mn10).

Our computer program was installed on a PLC identical with the one used in the laboratory, but placed at ArcelorMittal Hunedoara S.A. - Continuous Casting Plant (the classic method / Fuzzy).

In the first stage, the PLC had only the role to record, store and process the data, in order to validate its good operation, without being able to adjust the flow rate (the connection with the valves being interrupted), the cooling being made using the classic method. The recorded and stored data can be found in Annexes 6-12.

After validation of its good operation, the PLC was connected to the system (making the connection with the valves), and then 3 sets of castings were made using the program we have created.

So, for Ø250 mm, as a result of data recording and processing, we obtained the following diagrams, for the classical method and the Fuzzy method:

- The temperature difference compared to the liquidus curve;
- The casting speed;
- The valve location in all 3 cooling zones;
- The water flow rate in all 3 cooling zones.

As can be seen, the maximum temperature difference is 67°C, falling within the range of 0-70°C required by the technological process, the cooling being performed according to the shown parameters.

Similar experiments were carried out for Ø200mm and Ø180mm, respectively. In case of Ø200 mm, the maximum temperature difference was 60°C, and for Ø 180 mm, the maximum temperature difference was 50°C.

From the qualitative point of view, the diagrams differ (the classical method - the Fuzzy method), because at the classical method the graphs are presented as a discrete function (step), and at the Fuzzy method the graphs are continuous.

Either when using the classical method or the Fuzzy method, the graph shape is consistent with the actual situation, noting that a certain time period in which the "temperature variation" decreases is followed by an increase caused by the fact that the temperature in the centre of the steel ladle is higher, the "temperature variation" reaching a new maximum, logically followed by an decrease at the end of casting.

The Fuzzy method, by small time intervals (250 ms), enables the real-time optimization of the water flow rate required to cool the steel in the secondary casting area divided into 3 zones.

As can be seen in the flow rate diagrams afferent to the three zones, they comply with the technological proportionality (Example: for Ø180 mm, the total flow is distributed over the three zones, as follows: zone 1 → 40%, zone 2 → 40%, zone 3 → 20%), but also the minimum flow rate for the secondary cooling (for the same example: zone 1 → 80 l/min, zone 2 → 80 l/min and zone 3 → 60 l/min).

The flow rates are correlated with the casting speed and the type of profile. For Ø200 mm and Ø250 mm, either their technological proportionality or the value of the minimum flow rate at secondary cooling is different.

For Ø200 mm, three different flow rates are clearly identified due to the different technological proportionality compared to Ø180 mm (zone 1 → 33%, zone 2 → 40%, zone 3 → 27%).

Although the technological proportionality of the flow rate required for cooling the profile Ø250 mm is identical on the three secondary cooling zones with that of the profile Ø180 mm, the diagrams differ due to the minimum required flow rate (zone 1 → 60 l/min, zone 2 → 85 l/min and zone 3 → 105 l/min).

Conclusions

In this chapter, three major directions have been considered:

- The design and construction of an experimental stand to simulate the flow rate control in all three secondary cooling zones at the continuous casting of steel;
- The programming and implementation of the valve control PLC used to regulate the flow rate in real conditions;
- The research steps and methodology applied to improve the quality of the continuous cast semi-finished products with circular section by real-time cooling water flow rate control.

Firstly, the experimental stand was designed based on the actual situation in ArcelorMittal Hunedoara S.A., the construction of which was realised by using hardware elements compatible with the PLC. This stand is made up of certain elements that can ensure, when establishing the connections between them, a similarity in the control and regulation of cooling water flow rate in all three zones.

The PLC programming was done in two ways:

1. The first mode of programming, considered "classic", took into account only punctual elements of the existing situation, the temperature being measured at well-defined time intervals, and the program calculating automatically the position of the valve flap.

2. To eliminate the drawbacks identified in the first programming mode, we introduced the "Fuzzy" to enable the continuous calculation of the valve flap position.

Because the PLC is of SIMATIC S7 300 type, for the "classic" programming we used the STEP7 software, and for the real-time programming we used the FuzzyCotrol++ application.

To help the user, a friendly Scada command interface was designed using the WinCC application.

Under laboratory conditions, the functionality of the experimental stand has been validated, but also the logic of programming when using the two methods.

To test and implement the system designed and built, with the agreement of the management board of ArcelorMittal Hunedoara S.A., the program was installed in one of the PLCs of SIMATIC S7 300 type (Annex 13) existent in the Continuous Casting Plant. Compared to the laboratory equipment, for the practical operating conditions of the continuous casting plant, the potentiometer was replaced by S- type temperature sensor. Practically, three experiments were conducted for three different billet sections (Ø 180 mm, Ø 200 mm, and Ø 250 mm), using either the classic method or the Fuzzy rules method. The results were consistent with those obtained under laboratory conditions.

Following the experiments, it has been proven that the proposed Fuzzy solution is effective and far superior to the current flow rate control, being possible to be implemented relatively easily on any continuous casting machine without requiring major hardware modifications of the existing machine.

CHAPTER 7
FINAL RECAPITULATIVE CONCLUSIONS
ORIGINAL CONTRIBUTIONS
DIRECTIONS FOR FURTHER RESEARCH

Final recapitulative conclusions

The following final conclusions can be drawn from literature and from the results obtained during the research regarding the **Continuous casting process control using the intelligent Fuzzy system**:

1) The economic restructuring that occurred after 1989 led to the decommissioning of the 4 Siemens-Martin steelworks, the last one (OSM II, Hunedoara) being decommissioned in June 1999 and, therefore, the steel is currently made in oxygen converters and electric arc furnaces;

2) The electric steelworks that remained in operation after the economic restructuring are currently equipped with modern electric arc furnaces of EBT type (Eccentric Bottom Tapping), endowed with high and very high power transformers;

3) Equipping these steelworks with continuous casting machines and facilities for steel processing in casting ladles (LF and VD) provides optimum conditions for sequential casting and, as a result, they can be considered modern steelworks;

4) The duration of a heat made in an EBT arc furnace ranges from 45 to 75 minutes (very close to that of oxygen converters), being heavily influenced by the quality of metal charge and its degree of preparation, as well as the qualification of the operational staff;

5) The average productivity of about 100 tons/h is influenced by the heat duration, metal charge preparation and mostly by the iron content;

6) The duration of steel processing in such LF facilities ranges from 42 to 80 minutes, being influenced by the casting sequence structure and the synchronization of the steel-making and casting processes;

7) The tendency is to increase the quantity of steel cast in a sequence (i.e. the number of filled ladles);

8) The modern casting facilities ensure the casting of a wide range of semi-finished products of different sections, i.e. polygonal, circular and flat products;

9) The current trend is to cast semi-finished products whose section is as close as possible to the final one;

10) Regarding the quality of the metal charge, in the last 8-10 years there is an

increase in the skull share in the metal charge (the skull being domestic or imported, the iron content ranges within wide limits, which has a great influence on the specific consumptions - metal, energy, refractories, etc.).

11) The Fuzzy system, unlike a classical regulator, does not treat the information through a well-defined mathematical relation (regulation algorithm), but uses multi-rule inferences, based on linguistic variables;

12) The first applications of Fuzzy logic in regulatory systems appeared in 1975, and since 1985 the Japanese have used it in industrial processes to solve the management problems;

13) In Europe, the research on the application of Fuzzy logic in regulation began later; for example, in Germany the year of starting a systematic research is considered to be 1991;

14) The Fuzzy tuning systems can be considered recent and, therefore, the more research is conducted, the more new technical information can be provided in this field.

15) From the analysis of simple and multiple correlations established between the crust thickness (dependent parameter), the mould length and the pulling speed (independent parameters), the technological interaction among all these parameters stands out very clearly;

16) The mould length increase leads to an increase in the thickness of the solidified crust; on the contrary, the increase of pulling speed determines its decrease (following the reduction of specific amount of dissipated heat);

17) The obtained correlations can be used in the current practice and, especially, in research. Moreover, we consider they have potential to be improved and extended.

18) The surface quality of continuous cast billets is influenced by the properties of the lubricating slag, mostly by viscosity and surface tension;

19) The correlations established between the slag viscosity and superficial tension, considered dependent parameters, and the parameters of influence, represented by temperature and slag composition, are representative either from a mathematical or a technological point of view;

20) On the basis of the correlations we have obtained, it is possible to set the variation limits for the melting temperature and chemical composition of the lubricating slag, so as to obtain values within the technological limits for viscosity and surface tension;

21) Representative technological correlations, expressed analytically and graphically, have been established between the cooling parameters of the semi-finished products in the secondary zone of the continuous casting machine and the casting speed of the steel,;

22) Based on the graphical representations, depending on the steel casting temperature and the cooling water flow rate, we can choose the prescribed casting speed;

23) The proposed application, i.e. an original Fuzzy solution implemented on the existent structure of the control system of continuous casting, can lead to the elimination of cracks occurring in a billet cast in the secondary cooling zone;

24) In order to eliminate the cracks, we designed a Fuzzy system scheme which, analyzing certain parameter values taken from the process, is able to change the cooling water flow rate and the casting speed;

25) In the national and international literature there is no reference to an intelligent correction (IFS) of the water flow rate during the secondary cooling of the steel, with real-time adjustment per each cooling zone;

26) The rule bases were created using the experience of human operators and the information collected directly from the process at the continuous casting machine of S.C. ArcelorMittal Hunedoara S.A. (A.M.-HD);

27) The verification and confirmation of the rule bases and the designed Intelligent Fuzzy System (IFS) was made by simulation using the Simulink software;

28) The analysis of the simulation results shows that, regardless of the values

generated at the input, the IFS is making the necessary corrections for the casting speed and water flow rate in the secondary cooling zone, which confirms the validity of the system operation;

29) From the qualitative point of view, the use of the Fuzzy decision-making system is an efficient, practical and easy to implement method for the analysis of complex and non-linear phenomena.

30) The designed system can be adapted to the secondary cooling of all types and dimensions of the continuous cast billets.

Original contributions

Based on the study of literature on the subject of the doctoral thesis, on the laboratory and industrial experiments, on the mathematical and technological analysis of the obtained results, the original contributions are:

1) Making a Technological Synthesis about:

- The technological flow of steel-making and casting in high-power electric arc furnaces of EBT type (eccentric bottom tapping) with a capacity of 100 tons, steel treatment outside the furnace, i.e. in the casting ladle, LF *"Ladle-Furnace"* and VD *"vacuum-degassing")*, and continuous casting as blooms, billets and bars on a 5- strands plant;

- A very well documented synthesis on the use in industry / in the steel-making sector of the Intelligent Fuzzy System (IFS), considered recent and, therefore, the more research is conducted, the more new technical information can be provided in this field;

2) The use of EXCEL and MATLAB calculation software to obtain technological correlations by processing certain data from the literature, but particularly obtained from experiments; all the simple correlations (presented in this paper) are represented by polynomial functions of 1^{st} degree, 2^{nd} degree and 3^{rd} degree.

3) The use of EXCEL and MATLAB calculation software to process certain data from the literature, but particularly obtained from experiments, and obtaining simple and multiple (double and triple) technological correlations, representative either mathematically or technologically;

4) The obtained correlations, the simple ones, expressed by polynomial functions of 1^{st} degree, 2^{nd} degree, 3^{rd} degree and exponential, and the multiple correlations expressed by polynomial functions of 2^{nd} - 5^{th} degree and in combined forms are presented either analytically or graphically;

5) The analysis of correlations from the technologically point of view and setting the optimal ranges of variation of the technological parameters;

6) Determination of the optimal range of the slag viscosity within the limits of 0.4 – 1.4 Ns/m^2, which leads to the variation limits of the independent variables: CaO/SiO_2 = 0.7 - 1.14; (Al_2O_3+MgO) = 5.85 - 14.9% and T = 1200 - 1500°C;

7) The variation limits of the slag chemical composition, which determine the viscosity, are also consistent with the surface tension, more precisely they provide for this parameter values higher than $400 mJ/m^2$;

8) Between the cooling parameters in the secondary cooling zone and the continuous casting speed can be determined representative technological correlations, expressed analytically and graphically;

9) The determination, based on graphical representations, of the steel casting temperature and cooling water flow rate, for reaching the prescribed casting speed;

The experiments proved that the proposed Fuzzy solution is extremely efficient and far superior to the current flow rate control solution and it can be relatively easily implemented on any continuous casting machine without requiring significant hardware modifications of the existing one.

Directions for further research

Taking into account the results obtained in the elaboration of the PhD thesis, it is considered to be of interest to continue the research in the following directions:

1) Further experimentation of the designed Fuzzy system at the Steel Plant no. 2 – ArcelorMittal Hunedoara and comparison / verification of the obtained results by using Excel and Matlab correlations;

2) Application of the designed system to the continuous casting of slabs;

3) Designing a Fuzzy system (IFS) for steel-making process control over a flow consisting of EBT electric arc furnaces and ladle metallurgy (LF and VD).

Bibliography

1. E. Ardelean, „Turnarea semifabricatelor de oțel", Ed. Mirton Timișoara, 2004.
2. E. Ardelean, T. Heput, M. Ardelean, „Turnarea continuă a oțelului", Ed. Politehnica Timișoara, 2001.
3. E. Ardelean, A. Socalici, T. Heput, M. Ardelean, „Research regarding the temperature influence on continuous casting process", Scientific Bulletin of the „Politehnica" University of Timișoara, 2005.
4. N. Oargă, T. Heput, E. Ardelean, E. Popa, „Studiu privind defectele interne a semifabricatelor turnate continuu", Analele Facultății de Inginerie Hunedoara, Tomul III, Fascicola 1, 2001.
5. E. Ardelean, „Teză de doctorat", Universitatea Politehnica Timișoara, 2004.
6. E. Popa, „Teză de doctorat", Universitatea politehnica Timișoara, 2009.
7. F. Drăgoi, „Teză de doctorat", Universitatea Politehnica Timișoara, 2012.
8. I. Dragomir, „Teoria proceselor siderurgice", Editura Didactică și Pedagogică, București, 1962.
9. E. Popa, „Cercetari privind influența proceselor fizico-chimice-metalurgice ce au loc la interfețele cristalizor-zgură-oțel lichid", Ed. Politehnica Timișoara,2009.
10. Ș. Preitl, R. Precup, „Introducere în conducerea Fuzzy a proceselor", Editura Tehnică, București, 1997.
11. C. Voloșencu, „Reglare Fuzzy și neuronală", Editura Eurobit, Timisoara, 1997.
12. F. Angela, L. Marcel, „Quality control în die casting with neural networks", Proceedings of 1 st International Symposium on Neuro-Fuzzy Systems, pp 1-7, 1996.
13. S. Anghel, C. Cuntan, „Conducerea Fuzzy a procesului de răcire secundară la turnarea continuă", Sesiunea de comunicări științifice, Hunedoara 2001.
14. S. Anghel, N. Rusu, C. Cuntan, „Sistem expert pentru conducerea procesului de turnare continuă, bazat pe logica Fuzzy", Sesiunea de comunicări științifice, Petroșani 2001.
15. G. O. Tirian, C. A. Gheorghiu, T. Heput, R. Rob, „Fuzzy control strategy for secondary cooling of continuous steel casting", Innovative Ideas in Science 2016 IOP Publishing, IOP Conf. Series: Materials Science and Engineering 200 (2017) 012046 doi:10.1088/1757-899X/200/1/012046, (Scopus).
16. G. O. Tirian, C. A. Gheorghiu, T. Heput, C. P. Chioncel, „Control system of water flow and casting speed in continuousteel casting", Innovative Ideas in Science 2016 IOP Publishing, IOP Conf. Series: Materials Science and Engineering 200 (2017) 012047 doi:10.1088/1757-899X/200/1/012047, (Scopus).
17. V. Alexa, I. Kiss and C. A. Gheorghiu "The educational practices and e-learning courses in performing the laboratory works specifics to the hydraulics and pneumatics applications", Analecta Technica Szegedinensia Issue 3, pp 10-16, Szeged, Hungary, 2013, ISSN 1788-6392.
18. C. A. Gheorghiu and T. Heput "Studiu privind parametrii de influență a turnării continue asupra calității semifabricatelor", pp 1-6, HD-44-STUD, Hunedoara, Romania, May 2014, Annals of the Faculty of Engineering Hunedoara, (annals.fih.upt.ro).
19. C. A. Gheorghiu, T. Heput, "Controlul debitului apei de racire realizat cu ajutorul unui automat programabil PLC", HD-47-STUD Hunedoara, Romania, 2017, (fih.upt.ro).