Quality optimization of slab casting with use of software monitoring tool and statistical methods

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Abstract. The paper summarizes the basic analytical and empirical findings obtained during search of dependences of the influence of thermal process taking place during continuous casting of steel semi-finished products – slabs on their quality. The assessment of the quality of slabs uses the collected data and stores them for an effective evaluation of the measured qualitative quantities. The paper describes the proposal of the concept of solution and the function of software for thermal process assessment of the slab casting. Further analyses of possibilities of use of statistical methods for the assessment of the slab casting process are carried on with the possibility of slab quality prediction. The aim of the proposal of the above mentioned process is to provide to technological workers not only the possibility to analyze the process of casting, but also the long-time monitoring and optimization of the production. This approach brings at the process of slab casting important economic benefits.

Keywords: continuous casting, quality assessment, software, statistical methods, regression, optimization, economic benefits.

JEL Classification: C21

AMS Classification: 62J05

1 Introduction to the problem

Quality assessment at the continuous steel casting plant is an inseparable part of the metallurgical plant information system.

This assessment functions on the base of the data necessary for an effective evaluation of the dependence between measured values and quality benchmarks.

The system comprises data recording and filtration, data selection for the matrix of dependent and independent variables, data categorization and statistical method for search of dependences, data presentation and presentation of results of data analyses. The program system enables export of data matrixes into other statistical programs.

Due to the fact that an enormous amount of data is collected during steel casting and that parameters are sampled at the time interval of 10 seconds, the problem of data storage and their effective assessment becomes highly urgent. It is necessary to solve also several other problems in the information system that are related to the quality slab assessment. Firstly, the quality assessment of slabs is the assessment of the semi product, which is determined for further processing, and its insufficient quality appears only after rolling and completion of the final product. Secondly, not all the slabs can be assessed as cold rolled, because slabs are determined to be hot rolled. Therefore the majority of slabs will not pass through the quality inspection. Hence, prediction of the slab quality is needed. In order to predict the slab quality an archive of cast melts with the assessment of slabs is needed, as well as experience of technologists, who are able to create rules for prediction occurrence of possible defects.

For setting of the prediction system it is necessary to create an independent module monitoring the process of casting on the continuous casting machine (CCM), which further sorts out, aggregates and assesses the acquired data in relation to the quality of slabs, and preferably even in the relation to the final product – rolled sheet metal.

2 Motivation

This paper describes a possible approach to creation of such a monitoring program subsystem of the steel plant information system. It is necessary to design a data model with description of data for production monitoring.

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Basic processing functions assign the production data to the quality benchmarks using the above mentioned data model and the data warehouse. The result is creation of the data warehouse, statistical data analyses and their metallurgical interpretation. Hereunder we describe the monitoring program system LITIOS solving the tasks mentioned above (see figure 1). It has been realized in practice. In the future the data warehouse and the monitoring system [3] will be used for creation of the system of quality prediction.

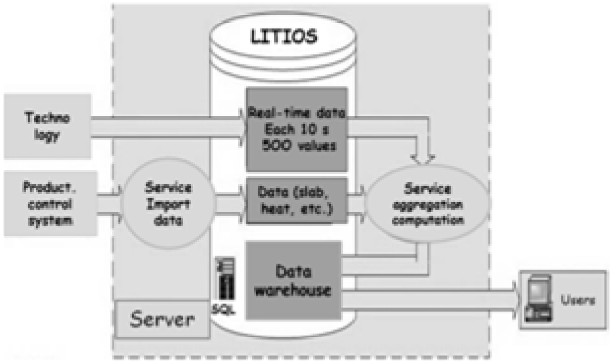

Figure 1: Architecture of the monitoring system LITIOS

3 The goal the project

The monitoring program system LITIOS and creation of the Data Warehouse [1], [4] at continuous casting plant is part of the project "Numerical & Stochastic Model of the Concast Steel Blanks of Rectangular Profile of the Czech Science Foundation", (GA CR Project No. 106/09/0940). The basis of the project consists in obtaining of new findings in solidification thermo kinetics of continuous casting of rectangular steel blanks, and also in creation of a mathematical-statistical method for prediction, numerical optimization and control of the process technology and quality of the final product. An original dynamic model will analyze the temperature field of continuous casting in real time. It will comprise a program for scanning all operational parameters on the caster. Calculation of the temperature field of the slabs will be confronted with the measured parameters on its interface. The stochastic optimization model [2] takes over values from the dynamic model, from the information system of the steelworks and rolling mill, including the data on the quality of the final products. On-line statistics will be ran over these data.

After determining the limit values of the deciding parameters (on the basis of a long-term file of data from the dynamic model) a control system will be elaborated and operation of the caster will be corrected according to the known current status of the caster and recommended limit values. Based on the data from the dynamic model, an on-line comprehensive quality prediction system will be developed, into which only real defects, including the causes of their occurrence, will be integrated. Graphical simulation of the prediction rules will be used to recommend immediate parameters for continuous casting.

4 System design

Since the control hardware and software of the caster are significantly heterogeneous and, furthermore, the casting process is continuous, it is necessary to ensure reliability of the communication tier. The communication tier enters the data in to its own temperature model using the XML/RPC standard with use of the standard TCP/IP protocol. It can easily be adapted to various hardware and software configurations ~~on~~ at the first and second levels of caster control – currently, drivers for Siemens and ABBPLCs exist, as well as for ORACLE and MS SQL databases. Synchronous data (recurring at regular intervals) is recorded every 10 seconds. Other asynchronous information, such as the melt number, chemical analyses, positioning of the tundish and opening of the tundish are read only when a new event occurs. The communication tier checks the validity of the data collected in this way, i.e. it verifies, whether it lies within the acceptable limits, or whether or not it has arrived. Erroneous data is replaced by previous correct data or by the so-called standard values, and then this complete and verified data is passed on to the dynamic on-line model. There are approx. 250 such quantities. The tier of the numerical model carries out the calculation of the temperature field and of other aggregated quantities, which it sends back to the steelworks information system. The temperature model calculates the values of approx. 250 aggregated quantities, so approx. 500 values appear every 10 seconds.

4.1 Data model

For optimizing the production from the point of view of the production quality at the continuous steel casting plant some particular items, so called attributes, were sorted out from the following sets. Based on the selected sets and attributes a diagram of the data model for the program system LITIOS was defined (see Figure 2).

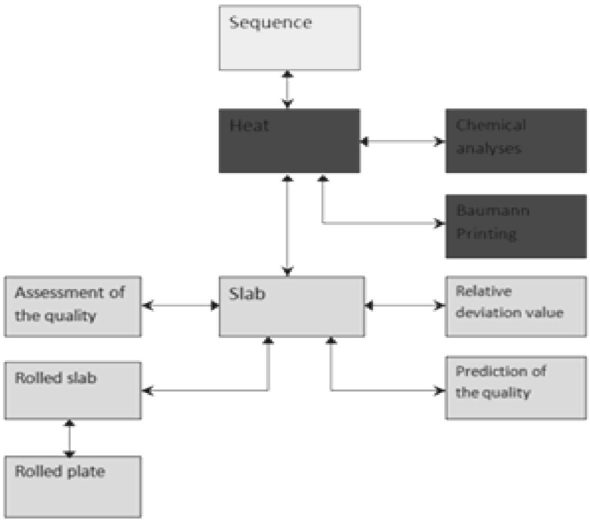

Figure 2 Diagram of the data model

Relational connections were made between the sets. The casting is divided into slabs, and slabs into segments (1m). The set containing the basic data about the slab (selected data from the set "slab production") was chosen as the operative one. For each slab exactly one record is formed. The metallurgical slab code is used as unique key for each record. Relation to another related set is made by the slab code attribute.

4.2 Viewing of functions

The system is modular and it is created on the base of the most advanced knowledge from the field of data technology and methods of data analyses. Views of the data characterising the slab are available for recording and data verification. Functions of the data selection are available in data analyses methods. Data are stored in the matrix of causes (measured production data) and effects (qualitative indicators). Statistical investigation can be made over such reduced data within the frame of the system LITIOS, from which data can be exported into other statistical software, as needed.

Viewing of functions:
- Data visualization and their graphic interpretation
- Searching by selected criteria
- Selection of castings and slabs – setting of the filter
- Selection of displayed items
- Setting of the format of displayed attributes
- Setting of the range for display of deviations of technological values
- Algorithm of search of implicative dependences by the association method
- Verification of hypotheses by the association method
- Exporting of displayed data into the data set (xls, csv, html and alike) for further statistical processing

Description of functions of the program and instructions for manipulation are contained in the user's manual of the system LITIOS.

5 Statistical analysis of dependences between the defects and the technological parameters

Due to the fact that the system LITIOS contains currently a sufficiently large archive set, it is possible to make an investigation of basic dependence by the single linear and quadratic regression, with the prerequisite of the relatively considerable rate of probability finding the dependences. We emphasize that we consider use of the correlation analysis here to be the "introduction into the problem" and further we suppose using more progressive methods of the relation between the parameter analysis and the given defect. Statistical analyses using the association methods, multiple logistic regression or relatively new branch of neuron nets, which tries to implement the data processing and operating by algorithms adapted from living organisms into current theories, are also available.

It is understandable that for search of relations between the defect and parameters of casting it is possible to use only the slabs, which were processed at the slab finishing mill. It was possible to detect and describe defects, or to state their „non defectiveness“. Approximately 19 000 such slabs were available only for the midterm of the last year. That is the set with the large evidence ability even further segmentation can be done. In our case we used four groups steel grades – deep drawing steel, structural steel with different contents of Si, and microalloyed steel.

As there were six types of monitored steels and the number of parameters of casting was twenty three, the total number of possible dependence of the „ steel grade –defect – parameter“ was equal to the product of 5x6x23, which represents altogether 690 combinations. It is obvious that testing such a big number of dependences would be technically very demanding and highly time consuming. It therefore was necessary to make selection of dependences in order to reduce their number from the most significant hundreds down to tens of cases.

For making sets with at least basic statistical predicative ability we took the number of cases of detected defects in the group concerned. As the minimum we have chosen the number of 100 defects, thanks to which the number of dependences has decreased several times.

The logical possibility of influencing the occurrence of the specific defect in the particular quality group by the particular parameter of casting was then use of another “sieve “. The dependence of the type „middle rolling crack versus cooling in the mould“, „non metallic inclusion versus secondary cooling,“ etc., were thus excluded from the selection.

5.1 Simple linear or quadratic regression

Before carrying out the analysis of dependence of parameters of casting the input data were also assessed from the point of their objectivity. Descriptive statistics were performed for each parameter based on the minimum and the maximum, or more precisely, on the number of cases in these outer limits. Using this assessment, admissible values of theses parameters were set.

Simple linear and quadratic regression was used for evaluation of dependence of occurrence of the given defect (inception) on the value of the particular casting parameter. From the equation of both of these dependences (linear and quadratic) one was chosen, which expressed the dependence with a greater degree of probability, i.e. the one that had a lower value of the F-test.

In the descriptive statistics the following is always valid:

- R2 - coefficient of reliability. It can oscillate within the limits from 0 to 1 and for the rough check we set that its value must be higher than 0. 5 for being it worth to deal with the dependence at all,
- F - value of the so called F test. In a simplified way it can be said that the value F subtracted from 1 and multiplied by 100 gives the probability indicator of occurrence of the particular dependence. In our case it is ideal, if the value is $F = 0.05$ or lower, that means that the dependence has the level of probability of at least ~~on~~ 95 % or more.

Values mentioned in the following graphs were obtained always in such a way that the spectrum of occurring values of the particular parameter (independent variable quantities) was into selected intervals (e.g. at the casting speed after 0.1 m.min-1) and in the given interval the percentage of slabs was counted with the found out deficiency. These values were then used as a base for calculation of linear and also parabolic dependence. The equation of dependence with a lower (better) value of the F test is shown in the graph.

5.2 Metallurgical interpretation of some dependences

In this chapter examples of results of the examined dependence are given. By the „metallurgical interpretation“ of these results ~~here~~ the authors intend to indicate that even statistical conclusions resulted from big sets must be read and interpreted by an experienced steelworker understanding technological and metallurgical dependences, which cannot always be recorded only by the statistical facts.

The following figures present graph of examples of the examined dependences with the given equation of the particular dependence (linear or quadratic) and the already commented coefficients R2 and F are shown. Graphs are completed by set intervals of input parameters with the percentage of defects in them and with basic values of the descriptive statistics. It is advisable to add the following to these dependences.

In principle oscillation marks are not regarded as a defect in our case. That means the case when the root of the mark is charged by the rolling crack. It is partly difficult and arduous to identify such defects, or as far as our estimation is concerned, there would be just only very few of such cases would be available for statistical analyses. Therefore the criterion (limit) was set up dividing them basically into „smaller and bigger (above limit)“. It can be stated in a simplified way that the quality of the slab surface is equal to the depth of the mark, the percentage of slabs in the above limited group can be a very good guidance for setting the optimal range of values of the examined casting parameter.

As for marks it is proper to add in connection with the secondary cooling that the percentage of deficiencies defects shown in the graph does not mean the percentage of the total production burdened by them, but only the percentage of slabs, which showed this crack on the cross section of the slab after its cutting by the flame cutting machine.

Oscillation Marks and the Casting Speed

The quadratic dependence (Tab. 1 and Fig. 3), in contrast to the linear one, shows a great probability measure (F = 0.006), with the minimum around the value of the casting speed 1,3 m.min-1.

Interval from	to	% def.
0.6	0.7	75.0
0.7	0.8	44.4
0.8	0.9	30.3
0.9	1	43.5
1.0	1.1	31.8
1.1	1.2	28.1
1.2	1.3	31.8
1.3	1.4	31.7
1.4	1.5	26.0
1.5	1.6	29.8
1.6	1.7	51.9

Table 1: Percentage of the above limit marks in intervals

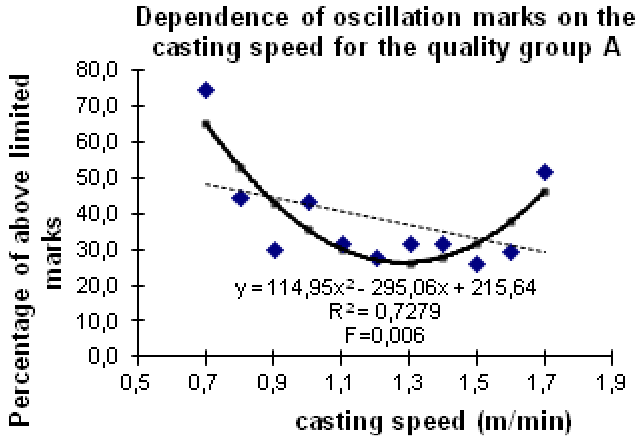

Figure 3: Oscillation marks and casting speed

However, after omission of the limit values (low number of cases), the dependence of the size of oscillation marks on the speed can be interpreted in the way that the size of the marks is in the speed interval from 1.0 to 1.6 m.min-1 nearly constant, favourable, and in the interval from 0.7 to 1.6 m.min-1 it has a slightly declining character (which corresponds also to the dependence of marks on the oscillation). From the point of view of this quality parameter of the slab surface it is therefore proper to avoid casting at the speed below the value of 0.7 m.min-1 (preferably below 1.0 m.min-1) and above 1.6 m.min-1.

Oscillation Marks and Acceleration

The linear dependence (Tab. 2 and Fig. 4) with the great probability measure nearly does not need any commentary.

Interval from	to	% def.
-0.01	0.04	45.4
0.04	0.08	43.8
0.08	0.13	52.9
0.13	0.18	54.1
0.18	0.22	57.6
0.22	0.27	60.3
0.27	0.32	58.6
0.32	0.36	50.0

Table 2: Percentage of oscillations marks in intervals

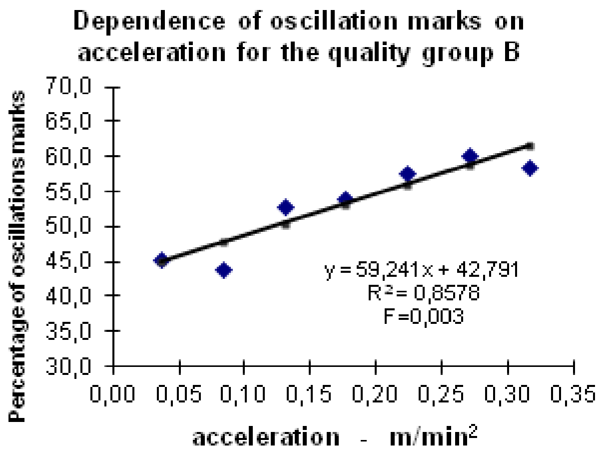

Figure 4: Oscillation marks and acceleration

It totally agrees with the logical reasoning about the influence of acceleration on the quality of the slab surface – increasing value of acceleration decreases (increases) the depth of marks.

Summary of the results

- In the first stage of the solution a total of 16 dependences of defects on the technological casting parameters were searched for. Linear and quadratic regression was used. In 9 cases out of 16 tested relations a statistically significant dependence was found.
- The relation, which seemed to be unreasonable – namely the dependence between formation of middle cracks and oscillation was intentionally investigated. The result was surprisingly "good", that is the biggest "non dependence" from the investigated relations.
- As far as unproven dependence is concerned, it was mainly the dependence of occurrence of non-metallic inclusions on the casting parameters.
- The correlation between the oscillation marks and the casting speed was proved. The dependences determined both for deep drawing steel and also structural steel made it possible to set clearly limits of the casting speed casting and mould oscillation, above which the depth of oscillation marks increases.
- The dependence between the oscillation marks and acceleration is very strong and clear, whereas at the same value of the acceleration a smaller percentage of deficiencies was registered in deep drawing steel.
- The dependence of middle longitudinal cracks on the secondary cooling has a clear and logical trend – with the increasing flow of water (intensity of cooling) the number of cracks on the slabs decreases. At the same time the limit, above which on the contrary a sudden increase of the crack occurrence appears, is clearly marked.

6 Economical benefits of statistical analysis

These results of statistical analysis enable correction of the selected casting parameters, which should reduce (or even eliminate) the number of defects on slabs by selecting the optimal values and limits of these parameters. In practice it brings essential economical benefits. The system of monitoring is useful at continuous production at the steelmaking plant. Long term statistical analysis and control is applied to setting up and updating of optimal values of the casting process parameters.

The above described approach to optimization of production of the process of continuous casting of steel is an inherent part of the information system of the steelmaking plant, and it is supposed to generate the following economical benefits:

- reduction of scrap factor,
- increase of continuous casting production,
- decrease of the production failure risk on the CCM (continuous casting machine),
- possibility of better identification of cracks and of their technological causes,
- necessary pre-requisite for creation of an on-line system for prediction of cracks.

The monitoring system LITIOS, statistical approaches and long term optimization process of production on the CCM form an inevitable part of production optimization both from technological and economical views.

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