Automated system of control and diagnostics of cast-steel defects in the mass production

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Abstract. To solve the problem of efficient control over technological process in the foundry the mathematical model is required, that would connect the the input and output parameters of the object. To collect the data on cast-steels defects an automated system was developed that greatly simplifies the process of technical control and allows the problem of process parameters optimization to be solved using the criterion of defects minimization in the cast-steels

1. Introduction

The technological process of mass production of cast-steels is a complex multi-parameter system, the state of which may be to assess by the quality of finished products. Examination of reasons leading to appearance of rejects and defects in the cast-steels associated with deviations in smelting and casting technology, properties of molding and core sand, forming conditions, as well as the design features of pattern equipment, is usually carried out based on the experience and intuition of process engineer and does not always allow the issue of stabilization and optimization of technological processes (TP) to be resolved quickly and in a timely manner. The role of this issue is particularly important in serial and mass production as material losses from reject, corrections, and mechanical processing of defective cast-steels are the heaviest.

Reject of cast products can be divided into two components – a reject of metal (steel) due to mechanical properties and chemical composition, and the presence of uncorrectable casting-process defects exceeding the critical characteristics in accordance with the State Standards (GOST), specification, customer requirements. The problems causing the reject due to steel mechanical properties are solved by the predictive models. It is possible to predict and control the mechanical properties of steel during its smelting. Having a reject prediction by one of the parameters, specifying the current values of the elements of the chemical composition and final conditions, it is possible to calculate the steel chemical composition, which is still possible to achieve for this melting and which will ensure the absence of reject. It was found that for the analysis of tendencies in the quality of cast-steels two key indicators from two groups of mechanical properties can be used – yield strength and impact viscosity on the V-shaped sample – KCV [1].
In the foundry practice the range of technological parameters variation is defined by GOST and the enterprise standards. It should be noted that these ranges are generally quite broad and comprise 10% of the nominal or more. Often during manual TP operation even these very broad ranges are violated. In addition, not all monitored parameters are sufficiently informative and their effective control is difficult.

Studies have shown that non-optimal sampling frequency, insufficient volume of samples and sample sizes are also the cause of deviations of technology parameters. Thus, maintaining a “hard” technological regime does not guarantee that it is optimal to obtain a minimal level of defects in cast-steels. Elimination of disadvantage of such regime is possible when using a “flexible” technology, which allows the production process (PP) to be adapted to changing external disturbances on the criterion of a minimal cast-steels defects [2].

Reliable results of assessment of the PP state in terms of identifying the reasons for casting-process defects and development of measures aimed at their elimination can be obtained by combined system analysis of cast-steels and a complex of technological testing devices [3].

2. Results and discussion

The most common defects of cast-steels of a complex configuration with a wall thickness 15-30 mm and weight up to 500 kg, manufactured in the single sand-clay molds with a lot of bars, are: hot cracks, blow-holes and porosity, clogging, scabs and burning-in. These types of defects are detected by external examination of cast-steel surface; their size can be estimated with a minimal use of measuring equipment.

The nature and size of surface defects provides information on the presence and size of internal defects of cast-steels. In order to identify correlations between the surface and internal defects of type “discontinuity” a selective quantitative visual and non-destructive testing of cast-steels before and after their machining was conducted by a special technique.

It was found that the correlation coefficients for the considered types of defects are $r = 0.71 \pm 0.86$ at the critical value $r_{cr} = 0.56$ and 95% of confidence probability.

The presence of significant correlations allows us to conclude that the results of monitoring of surface defects for this class of cast-steels and manufacturing methods can serve as an objective assessment of level of their defects.

To solve the problem of effective TP control in the foundry we need to have a mathematical model connecting the input and output parameters of the object. Information and diagnostic model (IDM) of the TP control subsystem on the level of cast-steels defects is built using mathematical and statistical methods of pattern recognition theory for two groups of parameters: parameters of technology and the level of casting defects [4]. The first task, solved during diagnosis, is to get information about the average level of defects (ALD) in the control batch of cast-steels for all considered types of defects.

For the collection of data on defects of cast-steels a formalized procedure was developed, which greatly simplifies the process of technical control and helps to organize the input of results into a computer in a dialogue mode. In this process the problem is solved, which almost eliminates the influence of a subjective perception of the operator-inspector on the assessment of signs of casting and process defects, both on the qualitative and quantitative levels.

The calculated data ALD of the control batch of cast-steels are used to diagnose the state of the TP and to make recommendations for its optimization.

In accordance with the terminology used in the pattern recognition, the diagnostic information consists of two components: system of features- assessments ALD for all considered types of defects and system of images-assessments of the TP state.

By the method of statistical classification [5, 6] from these components was formed a training diagnostic sample (TDS), for which the experimental sample data from the cast-steels connection ALD with the values of process parameters were used.

TDS is a table, each row of which contains the components of the feature and the corresponding image (Table 1).
Table 1. The form of TDS presentation.

| No. | Feature components | Values of TP parameter | Feature components | Normalized ALD value |
|-----|--------------------|------------------------|--------------------|---------------------|
|     |                    | 1                      |                    |                     |
|     |                    | 2                      |                    |                     |
|     |                    | 3                      |                    |                     |
|     |                    | …                      |                    |                     |
|     |                    | L                      |                    |                     |
|     |                    | 1                      |                    |                     |
|     |                    | 2                      |                    |                     |
|     |                    | 3                      |                    |                     |
|     |                    | …                      |                    |                     |
|     |                    | K                      |                    |                     |

Where:
- $X_{i,k}$ – value of the TP parameter;
- $Y_{i,K}$ – normalized value of ALD;
- $i = 1 \div N$ – number of TDS line;
- L, K – number of process parameters and types of foundry and process defects in TDS.

To provide optimal conditions for diagnosis in terms of recognizability during the TDS preparation the value of confidence interval for all considered parameters was taken into account.

TDS is used for pattern recognition – the probable technological situation, conditioning the appearance of a set of defects in the control sample. The control sample is a group of cast-steels for the aggregate defects of which the line with characteristic components is formed, for which the TP diagnosis was performed.

At this stage of technological situation recognition the Hamming distance is taken as a measure for the assessment of the control line proximity to TDS line [7]:

$$d_i = \sum_{k=1}^{K} \left| y_{i,k} - y_{j,k} \right|$$

where $y_{i,k}$ – normalized values of ALD for $j$ control batch.

During the preliminary recognition usually the subgroup of image compounds is detected, i.e. several technological situations, in which appearance of a set of casting-process defect corresponding to the control sample, might occur.

For clarification of the content of the situation and its quantitative assessment the identified subgroup of attributes is subjected to the repeated recognition. In this case, Euclidean distance is taken as a proximity measure of lines [7]:

$$d_i^2 = \sum_{k=1}^{K} \left| y_{i,k} - y_{j,k} \right|^2$$

The line of images in the diagnostic table, which has the lowest value $d_i^2$ is a probable technological situation conditioned the emergence of defects in the control sample.

To use the diagnostics results recommendations should be provided helping to develop optimal control actions on TP.

To achieve a higher level of technological situation recognizability the change in the nature and content of the TDS is required along with the accumulation of information. In order to adapt IDM to changing production conditions the subprogram of its self-education is organized. Implementation of the self-educating subprogram consists in the update of data and elimination of redundant information. Synthesis of new diagnostic line image-feature takes place, based on the analysis of a series of control samples.

In cases when the occurrence of defects depends on the violation of the technological process and can not be associated with control actions, the parameters, which do not correspond to standards, are identified, and percentage of reject due to violation of the technology is calculated.
The TP control subsystem on the level of casting defects is mainly used for PP stabilization, identification of tendency for TP rejection and generation of control actions aimed at their elimination. A significant delay of information due to the interval duration from the beginning of its formation until its inspection after the preliminary cleaning and large volume to be controlled is not always possible to effectively use the subsystem for PP optimization.

A promising method to diagnose PP is to use the complex of technological probe-sensors having a greater sensitivity to the formation of defects than the industrial castings. In this case, the information about the TP state, deviation of process parameters or their unfavorable combination can be obtained much earlier, before the increase in reject of cast-steels or their defects. This information will help to optimize the parameters of TP through preventive measures of technological and organizational character aimed at PP correction.

In the analysis of defects and cast-steels reject in the foundry shops it was established that during casings into of expendable sand-clay molds 80% of all types of defects are blow-holes and porosity, hot cracks and clogging.

Qualitative and quantitative diagnosis of PP according to the listed types of defects is carried out by a complex consisting of four technological samples [3]. These probes help to reproduce specific types of defects and obtain their quantitative evaluation based on the combination of PP variables factors.

The first two samples in the complex, designed to detect propensity for hot cracking in castings, depending on the steel chemical composition, temperature and casting speed, the deceleration degree of linear shrinkage by the mold.

The first technological sample represents five bars of different lengths with elements of deceleration of shrinkage by the mold common thermal node. The critical rod length corresponding to its destruction at different PP factors is determined by calculation [8, 9] and experimentally. The Assessment of PP trends to hot cracking is the number of bars with hot cracks in the conjugation with the thermal sample node.

The second technological sample is a traditional grille with a thermal node and a massive middle core, where the formation of hot crack takes place, by the degree of crack opening the alloy hot brittleness is evaluated.

The third sample provides a quantitative differentiated assessment of the causes for gas defects. It consists of two annular elements with a common gating system. The total area of the gas defects in each element, determined by X-ray diffraction method, is proportional to gas generating capacity of the rods made of the same sand and sodium silicate mixture, as well as the degree of steel deoxidation.

The last sample serves for the probabilistic assessment of the causes of clogging, depending on the physical and mechanical properties of the molding sand and conditions of forming [10]. A quantitative measure of clogging formation probability is the number of the destroyed sections of various heights of the sample print after its removal from the half-mold.

All technological samples are mounted on the molding plate and produced simultaneously with the production cast-steels. The first three samples are poured with metal and analyzed for the position of castings shake-out, the result of the fourth sample is obtained right after the completion of the forming process.

The diagnostic information characterizing PP includes two components: quantitative estimates of the level of defects in samples and values of technological parameters. From these components based on the experimental data a training sample (TS) is formed, further used for evaluation of probable PP parameters PP, conditioned the appearance of a certain level of samples defects (Table 1). TS has \( N \) lines, the number of which is specified in the course of data storage. Each line is characterized by assessments of the level of sample defects and PP parameters. Parameters \( L \) contain the most significant ones influencing the defects appearance: the temperature and the casting speed; content of carbon, sulfur and residual aluminum in the steel; humidity, strength, gas permeability, compressibility, and the content of organic impurities, friability – for the molding sand; strength and gas permeability and friability – for core sand. The listed parameters are selected according to the results of statistical investigations of the reasons of defects in steel cast-steels, they are characterized
by high information content, absence of meaningful correlations in the field of their determination and the possibility for their effective change.

Information and diagnostic model of the TP control subsystem as for information on technological samples defects is similar to the control subsystem model for the level of defects in cast-steels. The information characterizing the PP state, is composed of two components – quantitative estimates of the samples defectiveness and process parameters values.

Analysis of the current state of PP is conducted the following way: the information on the set and quantitative characteristics of samples technological defects obtained at some point in time, is entered into the computer, running the diagnostic algorithm. The algorithm provides a comparison of the presented levels of defects in samples with the possible situations of the training sample. Any situation from the recognized ones is characterized by a well-defined set of PP parameters, purposeful change of which reduces defects in the samples and correlation associated with it the level of casting defects [3].

Usage of samples depends on the value and nature of external disturbances. During the stable low level of casting defects and small external disturbances the complex of samples is used one – two times for the flow in a shift.

3. Conclusions
Experimental and industrial tests of the quality control system of casting showed recognition rate up to 80%, which is acceptable for solution of technical problems.

For the development of the system and production of more informative data on the casting defects it is recommended the introduce innovative non-destructive control methods (NCM) – X-ray tomography on the basis of the betatron to control internal technological casting defects in the cast-steels of type “discontinuity” (now they are not controlled) and thermal unit based on the infrared thermal imager for detection of surface cracks (the control is difficult has a selective character). These NCMs allow the complete additive control to be performed in the flow of internal and surface defects of cast-steels and store these data in electronic form for each manufactured casting. This information will complement the product passport with new data, raise control of castings and products manufacturing to a new level, with analysis of various components failure during their operation, mathematical modeling of components cast structures, calculation of their reliability and lifetime prediction.

Development and implementation of models into production and parallel automation of production control processes (decision-making) will minimize the impact of human factors on the quality of products, stabilize and optimize the production process of cast products.

4. References
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