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ORIGINAL ARTICLE

Automatic system for intelligent support of continuous cast billet production control processes

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Abstract The development of an automatic system for the intelligent support of continuous cast billet production control processes is described. The motivation for the development of the system is that it should improve the efficiency of production facilities and minimize the possibility of producing inferior and unacceptable quality products. A theoretical analysis of the information relating to the quality control of the processes and the finished products is presented, enabling the identification of the sources of information, methods of information acquisition, and techniques for processing it to ensure improved product quality. The development of mathematical support is described for a program analyzer that automatically and reliably identifies the defects and quality of the continuously cast billets. The application of graphic information acquisition and processing techniques concerning the quality of the metal products is also presented. The development of mathematical and software support is described for the set point adjustment module operating in the automatic system for the intelligent support of the multistage continuous cast billet production control facility. This module makes use of adaptive fuzzy trees with dynamic structures to provide scientifically grounded analysis of factors causing billet defects. The introduction of the developed systems, including practical issues, into the operation of a production facility is explained. The study identifies the general lack of automatic systems that encompass and control the whole production chain on the basis of product quality. Typical savings resulting from quality improvements in a continuous cast billet production facility can approach a million rubles.

Keywords Cast billet production · Quality control · Fuzzy set decision-making · Automatic production systems · Billet defect identification · Image analysis

1 The scope of the problem

In Russia, the modern industry presents new requirements in multistage manufacturing control systems determined by the introduction of new priorities outlined by the country's state policy. One such priority is the development of information and telecommunication technologies representing an essential part of automatic control systems for large industrial enterprises. The application of new modules in automatic control systems for multistage manufacturing processes improves the efficiency of production facilities and minimizes the possibility of inferior quality products.

From the viewpoint of control theory, multistage technology of continuous cast billet production is a complex subject. This type of technology requires a control system which provides real-time monitoring of product quality as well as intelligent support of decision-making in the production control processes.

Development and implementation of new modules, supplementing the control systems already in operation, make it necessary to use graphic information obtained in the process of quality assessment of finished and semi-finished products.

Specialists in automatic process control systems have gained considerable experience in the field of theory and the practical application of graphic information and decision-making. The issues of image acquisition, processing, and segmentation have been discussed in papers by both foreign and Russian scientists. The papers of Gonzalez and Woods [1], Shapiro and Stockman [2], and others determined the development of the mathematical theory in the field of graphic information improvement and segmentation. The field of

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decision-making on the basis of tree structures was developed by Quinlan [3], Janikow [4], Hastie et al. [5], and Berestneva and Muratova [6]. In the field of practical application of fuzzy sets and fuzzy logic theory, the papers of Jantzen [7], Timothy [8], Esposito et al. [9], and Dulicheva [10] are relevant.

However, in spite of numerous studies and papers in the field of automatic process control systems of continuous cast billet production, there are still some urgent problems to be solved:

- The lack of automatic systems to provide control of the complete processing chain on the basis of information about product quality.
- The lack of graphic information acquisition and processing techniques concerning the quality of metal products using low-contrast images containing irregular (shaped) elements.
- The lack of application program packages for intelligent support of decision-making in multistage manufacturing automatic control systems developed using adaptive fuzzy decision trees with dynamic structures that consider product quality.

2 Objectives of the research

Taking into account these problems, the main objective of this research was to reduce the incidence of low-quality products by using an automatic system of intelligent support for multistage manufacturing control developed on the basis of adaptive fuzzy decision trees with dynamic structures.

To achieve this objective, the authors had to:

- Carry out theoretical analysis on information on the automatic control system for continuous cast billet production to determine the sources and methods of acquiring and processing graphic information;
- Develop mathematical support for the continuous cast billet quality analyzer including a formal description of the area boundaries of the template image, algorithms to improve and segment it, and a fuzzy tree structure of billet defect classification using the quality and quantity of irregular (shaped) objects;
- Develop the structure of the automatic system for intelligent support of continuous cast billet production control. In addition, to develop the mathematical support and software for the decision-making module used in process set point adjustment in the automatic system for intelligent support of multistage continuous cast billet production on the basis of adaptive fuzzy trees with dynamic structures; and
- Develop organizational and technical solutions for the operation and maintenance of the automatic system including production engineer workstation design, selection of a hardware platform for program analyzer operation, and estimated economic efficiency of the operation of the developed modules.

The investigation is concerned with the automatic system of quality control for multistage continuous cast billet production. The focus was mainly on information, mathematical and software support including the mathematical description of graphic information, and adaptive fuzzy decision trees with dynamic structures developed for the intelligent support of decision-making processes for online correction of control actions.

3 Theoretical analysis of information on the automatic control system for continuous cast billet production

As a result of the theoretical analysis, it was found that its architecture was made up of automatic control systems for the various process stages including steel manufacture in electric arc furnaces, steel treatment in the ladle furnace, and steel casting in the billet continuous casting machines. The process control subsystem specifies the operating schedule and product quality control parameters. The subsystem contains all the technological regulatory information for determining and forwarding process requirements to machine automatic process control systems for each sub-stage of the production program [11]. The information is transferred to the quality control system. To establish the main components of all the processes of the technological chain of continuous cast billet production, the authors carried out a complex analysis of the control system for each process stage. The analysis was carried out on the basis of experimental observations and a study of the technical instructions, standards, and metrological data. The main source of information for making decisions on the cause of inferior quality billets is the heat log completed for each production stage [12].

The heat log contains the results of the visual test of the template. The template selection scheme for square and rectangular billets is given in Fig. 1. The technological instruction states that the template must be selected after the fifth billet of the first batch. If necessary, an extra template selection of other billets from any other batch can be carried out. When fulfilling some critical orders, templates are taken from every second billet of the batch.

The acquired template is sent to the plate and sheet laboratory where it is processed and evaluated according to OST 14-4-73 and OST 14-1-235-91 [13, 14]. However, the information about the quality of the billet estimated in the lab is quite subjective. Analysis of the results made it possible to identify

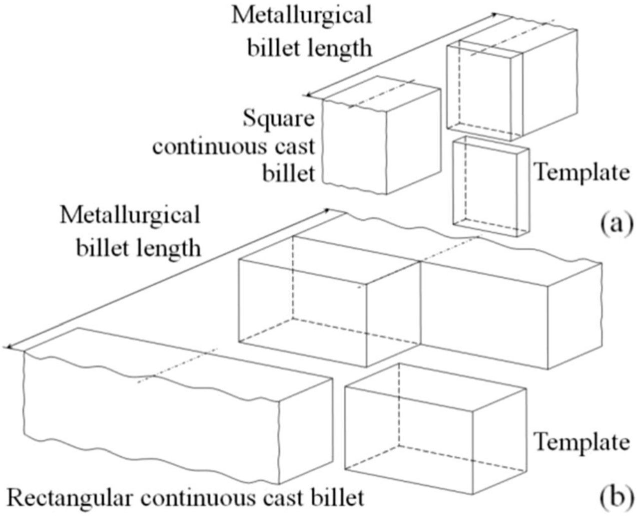


Fig. 1 Common scheme of template selection for a continuous cast billet: **a** a square billet; **b** a rectangular billet

the following drawbacks in the control system for continuous cast billet production:

- The lack of an automatic system developed for continuous cast billet quality estimation, which resulted in generating data of low reliability, integrity. and relevance.
- The lack of communication with the quality control departments because the information about billet quality was not reliable enough.
- The lack of mathematical support for the improvement and segmentation of continuous cast billet template images and their sulfur prints, defect location in these images, and classification of the discovered defects.
- The lack of program analyzers developed for automatic processing of graphic information for decision-making in the technological process.
- The lack of an integrated scientific decision-making system structure for the interdependent processes of steel melting, secondary steelmaking (processing in a ladle furnace), and continuous casting of steel, which results in control mismatching at each stage.

The disadvantages above make it difficult to organize efficient control of continuous cast billet production using information about the final product quality. It results in the incidence of inferior quality billet at about 0.03 % of the total bloom output because of the reduction in the efficiency of the metallurgical facilities.

4 Mathematical support for a continuous cast billet quality analyzer

To analyze the graphic information, researchers of the OJSC "Magnitogorsk Iron and Steel Works" laboratories collected 71 images of sulfur prints and 384 template photos. The acquired information is classified in Fig. 2.

The information is represented by the images given in Fig. 3. The defects are represented by irregular (shaped) objects of low brightness. In total, the defects shown in Fig. 4, namely dot non-uniformity, axial porosity, perpendicular billet edges and blowholes, were considered.

To develop a mathematical description of the template image, we introduced the following assumptions that did not change either the semantic or physical essence of the object under study:

- The color image has a dot matrix drawing (more than three hundred dots per inch).
- The image is a parallelogram, and an affine coordinate system is introduced for this image with a unit segment of one pixel.
- The image is positioned according to the rule that the upper edge of the image is aligned with the billet side plane located sidewise on the minor radius of the billet continuous casting machine.
- The color image is matched with the location scheme for the internal defects of the billet; an oblique system of coordinates with Δh increments is introduced into the image to decompose the photo into regions with uniform brightness.

The mathematical model of a color image consists of:

1. An analytical description of the image area boundaries (Fig. 3c):
   - The dot non-uniformity region ABFE given by:

$$\begin{cases} y\cdot ctg(\beta)\le x\le\left[y-a\dfrac{\sin(\alpha-\beta)}{\cos(\beta)}\right]\cdot ctg(\beta), \\ x\cdot tg(\alpha)\le y\le x\cdot tg(\alpha)+0,84\cdot b\dfrac{\sin(\beta-\alpha)}{\cos(\alpha)};. \end{cases} \tag{1}$$

   - The axial defects region MNOP given by:

$$\begin{cases} \left[y-0,4\cdot a\dfrac{\sin(\alpha-\beta)}{\cos(\beta)}\right]\cdot ctg(\beta)\le x\le\left[y-0,6\cdot a\dfrac{\sin(\alpha-\beta)}{\cos(\beta)}\right]\cdot ctg(\beta), \\ x\cdot tg(\alpha)+0,4\cdot b\dfrac{\sin(\beta-\alpha)}{\cos(\alpha)}\le y\le x\cdot tg(\alpha)+0,6\cdot b\dfrac{\sin(\beta-\alpha)}{\cos(\alpha)};. \end{cases} \tag{2}$$

   - The blowholes region ABCD–(ABFE ∪ MNOP) where a is the billet width in mm, b is the billet height in mm, and $\alpha–\angle XOX'$, $\beta–\angle XOY'$.

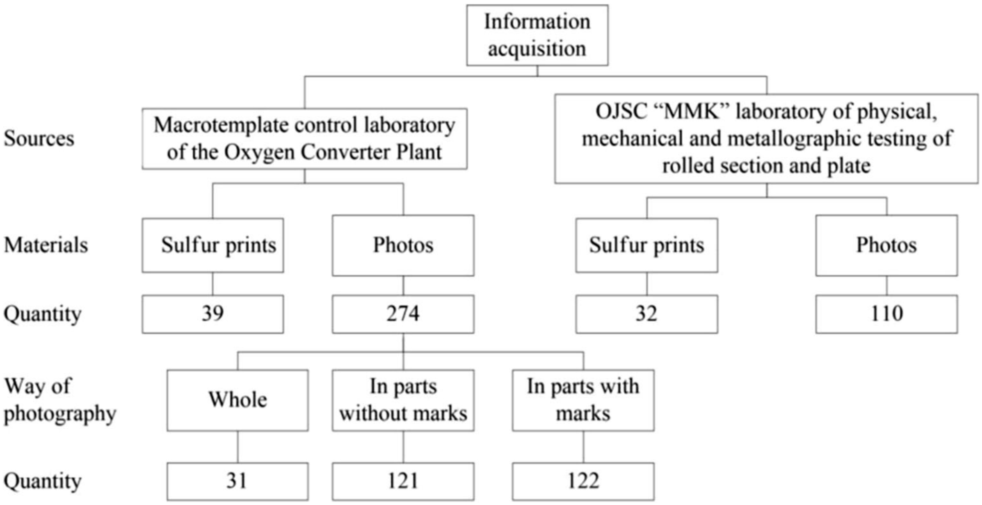


Fig. 2 Classification of source information for analysis

2. The analytical description of the image color matrix is given by:

$$f(x,y) = \frac{c(x,y)}{c_{\max}}, \tag{3}$$

3. Uniformity criteria of the irregular (shaped) region:

$$|f(x,y) - f(x,y+1)| < G, \tag{4}$$

where G is the constraint constant determined empirically.

4. Expressions for the property calculation:
   - Image recognition criterion:

$$f(x,y) < Q. \tag{5}$$

   - Image contrast criterion:

$$\max_{x\in[0,a],y\in[0,b]} \{f(x,y) - Q\} < G_{кр}, \tag{6}$$

where Q is the value of the Strehl ratio, and $G_{кр}$ is the critical difference between the values of the relative color of the point and the Strehl ratio, which makes it possible to select a uniform region.

5. Equation for noise-suppressing mask on the image:

$$f'(x_0,y_0) = \sum_{x=x_0-1}^{x_0+1} \sum_{y=y_0-1}^{y_0} f(x,y) \cdot H(x,y), \tag{7}$$

where $f'(x_0,y_0)$ is the function of the relative color after noise suppression at the point (x_0,y_0), and H is an array of weight coefficients.

6. Equation for image binarization:
   - Preliminary image inverting:

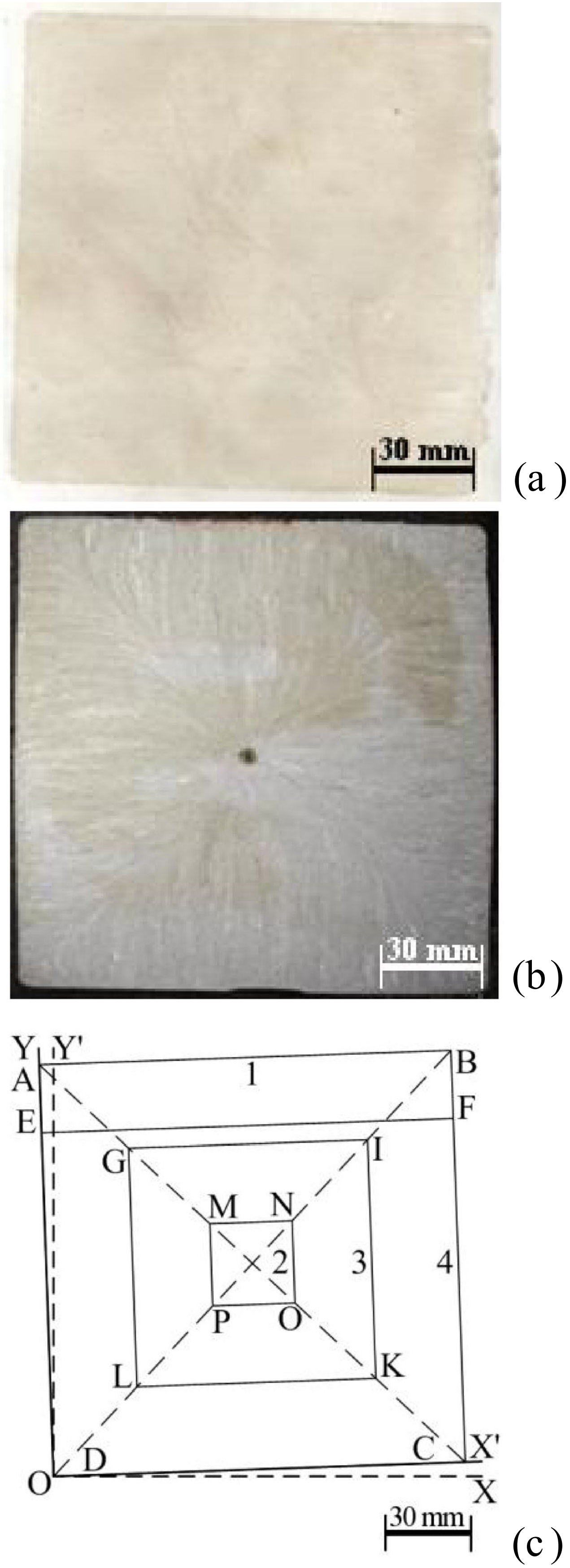
$$I(x,y) = \begin{cases} 1 - f'(x,y) & \text{when} \quad Q - f'(x,y) > h, \\ 1 - Q & \text{in all other cases;} \end{cases}. \tag{8}$$

   - Image binarization:

$$B(x,y) = \begin{cases} 1 & \text{when} \quad I(x,y) > 1 - Q, \\ 0 & \text{in all other cases.} \end{cases}. \tag{9}$$

A method of image acquisition was developed to improve the reliability of the data. The scheme for the developed method is given in Fig. 5. The developed mathematical description for images comprising the database made it possible to turn from unformalized descriptions of image objects to their quantitative prototypes (Figs. 6 and 7).

Formalized quantification of the estimation results made it possible to develop an automatic classification system of the internal defects in continuous cast billet. A classification algorithm was developed on the basis of the C4.5 algorithm and the algorithm for improving the decision-making process using a fuzzy decision tree. To make a forest of fuzzy decision trees that take into account the classification table results using attributed quality characters, the research group introduced linguistic variables to describe defect parameters. These included width, length, relative width, relative length, defect area, maximum area, relative area, length/width ratio, width/length ratio, quantity, and belonging to regions.



◀ **Fig. 3** Graphic product quality information fed into the automatic process control system: **a** sulfur print, **b** template photo, **c** the scheme of template image decomposition into parts where $f(x,y)$ is the value of the relative color at the point (x,y), $c(x,y)$ is the color digital code at the point (x,y), and $c_{\max}$ is the maximum color code in the image

Figure 8 shows a membership function of a linguistic variable “Defect size” obtained from expert evaluation by laboratory technicians who have been working in this field for more than 10 years.

If the defect size in Fig. 8 is referred to as small, it means that all processes worked steadily; if it is referred to as average, it is necessary to introduce some minor corrections into the process variables; and if it is referred to as large, it is necessary to take urgent measures and interfere in the process as the billet is of inferior quality and cannot be further processed or shipped to the customer.

The tree structure developed to estimate the axial porosity of a continuous cast billet is given in Fig. 9. The complete forest of fuzzy decision trees contains from 800 to 2,000 leaves. Branches in Fig. 9 were marked for a defect of average size, a part of which is located in region 3. If 10 % of the defect is located in region 3, the template grade of membership to the target class (quality template) is 0.334, corresponding to 2.5 points using the OST classification.

However, obtaining a quality evaluation on the basis of only the decision tree is not sufficient for making a decision on

Fig. 4 Element of a sulfur print containing characteristic defect categories and shapes on a scale of 1 in 8: *a* dot non-uniformity, *b* cracks perpendicular to the wide side, *c* longitudinal cracks

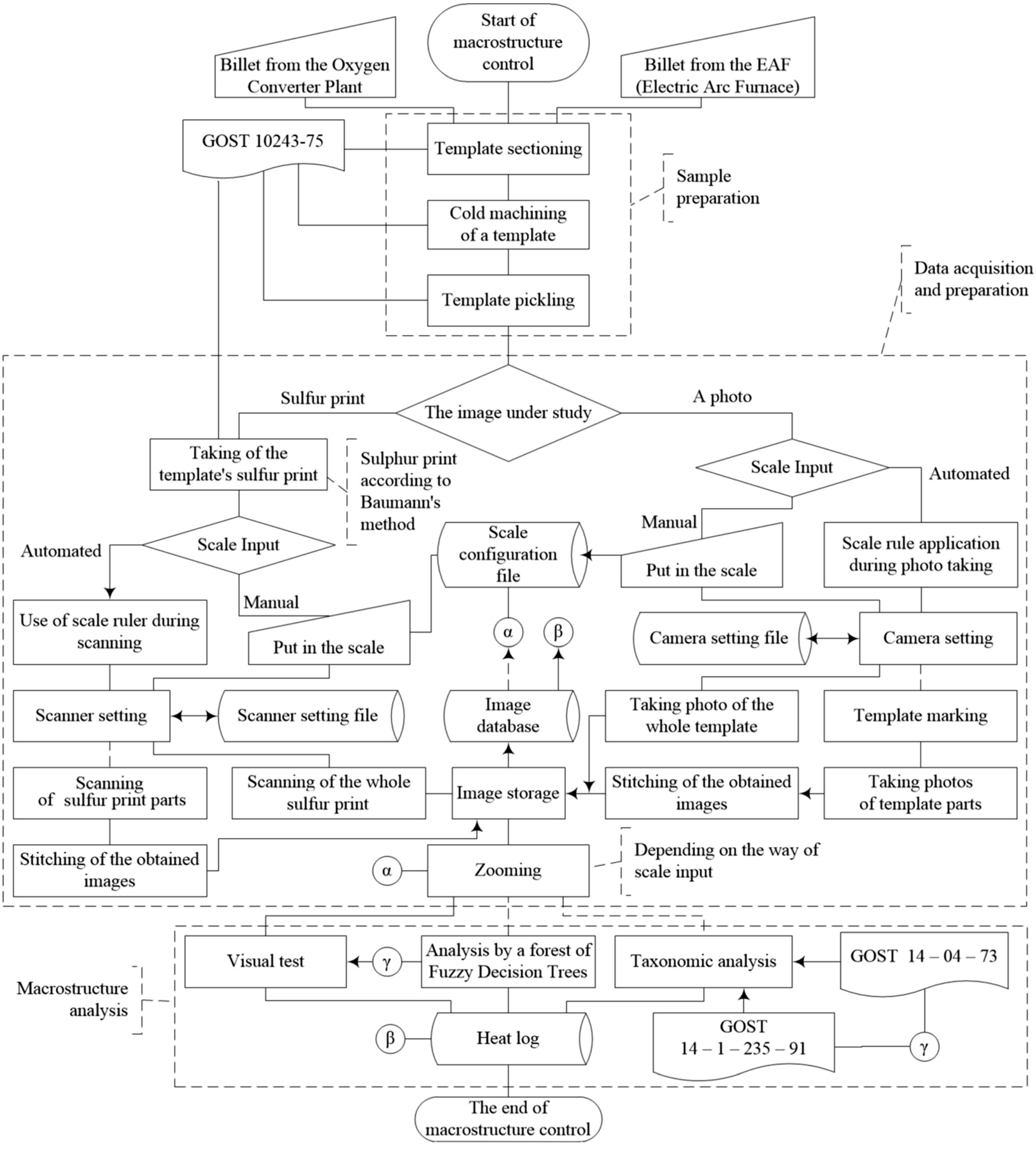


Fig. 5 The scheme for the data acquisition method on the quality of continuous cast billet for the automatic process control system

the values of the variables of the production process, which is why it was decided to develop mathematical and software support for a decision-making module. The module will be responsible for making decisions on set point adjustments.

5 The structure of the automatic system for intelligent support of continuous cast billet production control

Taking into account the structural features of the automatic control system for continuous cast billet production as well as

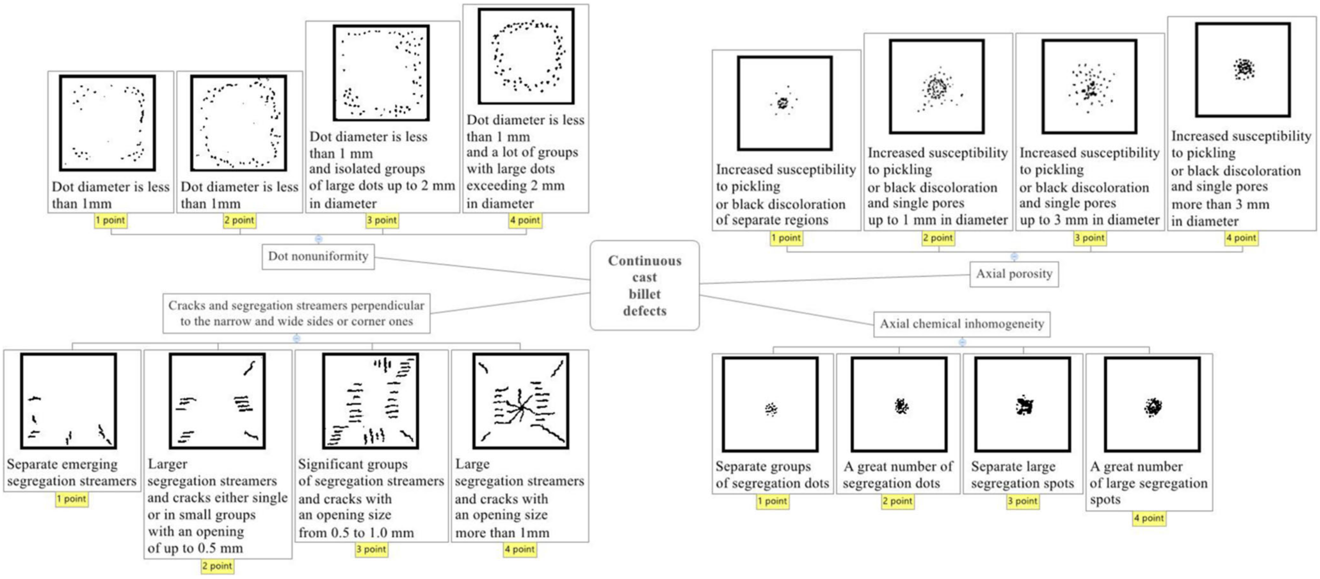


Fig. 6 Unformalized description scheme for irregular-shaped objects on the template image

stable batch production, the structure of an automatic system for the intelligent support of continuous cast billet production control at the electric steel making shop of OJSC "MMK" was developed (Fig. 10).

In the global loops of the EAF and the ladle furnace (1, 2), the controlled object is liquid metal and in the billet continuous casting machine (3), the controlled object is a billet. A sample in the form of a template and (or) its sulfur print is transferred to the module for automatic evaluation of continuous cast billet templates. Having processed the image, the module sends the expert analysis of template surface macrodefects to the decision-making block for set point adjustment of the various stages of the continuous cast billet production chain [15].

The decision-making block generates instructions on corrections to be made in the control system which are transferred, time-lagged, to the blocks of mathematical models of global loops processes.

A service simulating test is carried out on the basis of the numerous operating process technology models [16–19]. The results of the service simulating tests on the adjusted data and forecasted billet quality are transferred to each decision-making block. The decision on set point adjustment is made by an expert in the scientifically based results of modeling and forecasting. The decision is transferred to each subsystem of the global loop, with time lags resulting from the time intervals necessary for performing operations on further stages of the liquid metal, billet, or sample processing.

Taking into account the minimum and maximum values of the lag time as well as the processing time for the heat in each machine, we established that it would take the signal for the set point adjustment from 5 to 7 heat cycles to reach the EAF, from 3 to 7 heat cycles to reach the ladle furnace, and from 2 to 3 heat castings for the signal to reach the billet continuous casting machine.

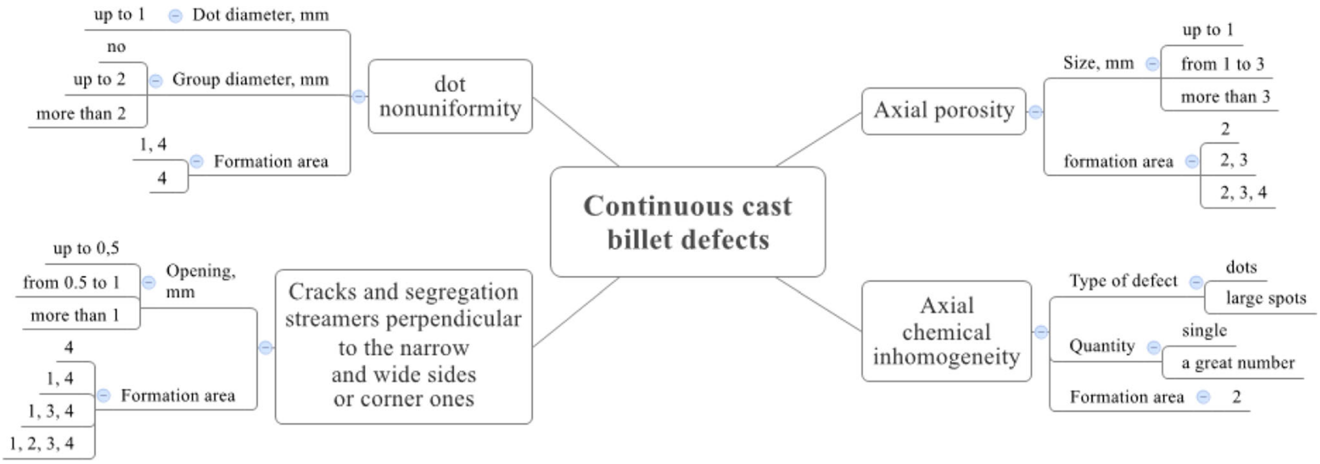


Fig. 7 Unformalized and formalized description scheme for irregular-shaped objects on the template image

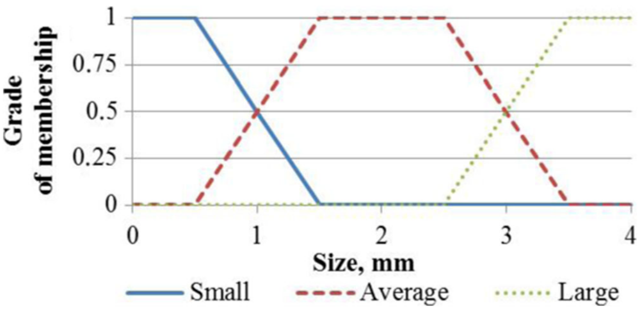


Fig. 8 Graph of membership function for classification of billet defect

Provided that the billet batch production consists of the melting, processing, and casting of 25–50 heat cycles per batch, the proposed technological advancement makes it possible to reduce the incidence of inferior quality billets.

The following symbols are introduced in Fig. 10: block 1 is the steel melting control loop in the electric arc furnaces, block 2 is the melt processing control loop in the ladle furnaces, block 3 is the continuous casting control loop in the billet continuous casting machines, Z_i^j are initial set points for the *i*th machine, $Z_i^{K_j}$ are the adjusted initial set points for the *i*th machine, Z_i^{in} are the calculated values of the local control loop modes for the *i*th machine; V_{out} is the billet yield, I_3 is the sample in the form of a template and (or) its sulfur print; $\{O_E\}$ are the expert evaluations of macrodefects on the template surface by OST classifications, K_i is the instruction to adjust set points for the *i*th machine, O_i is the forecast macrodefects evaluation for the *i*th machine, $\{Z_i^p\}$ are parameter values of the local control loops for the *i*th machine obtained as a result of process simulation, and ΔZ_i^j are the adjusted set points for the *i*th machine, where *j* is the set point number and *i* is the machine symbol. In the global loops (1, 2, 3), the process model block accepts instructions to adjust the set points.

An adaptive fuzzy tree with a dynamic structure was developed for the decision-making block (Fig. 11). The following factors were determined as linguistic variables for the decision-making trees on possible causes of defects: heat, weight, metal temperature after tapping from the EAF, metal temperature after secondary treatment, metal temperature in the tundish, metal oxidation/deoxidation state, steel casting speed, and steel chemistry.

Taking into account that the leaves of the developed tree are as depicted in Fig. 11, the decision makes use of only the two branches marked by the dashed line. Provided that the water consumption in the secondary cooling zone is 444 l/min and the casting speed is 3.5 m/min, the decision 0.14 belongs to the upper branch (A) and 0.86 belongs to the lower branch (Fig. 12). For this decision, one can calculate the grade of membership in the quality billet class:

$$\delta(D_j) = \frac{(77.81{\cdot}1 + 5.05{\cdot}0){\cdot}0.14 + (13.2{\cdot}1 + 5.71{\cdot}0){\cdot}0.86}{(77.81 + 5.05){\cdot}0.14 + (13.2 + 45.71){\cdot}0.86} = 0.357. \tag{10}$$

This grade of membership corresponds to 2.5 points using OST [14, 15]. The billet is considered to be of good quality if this value is less than 2 points. Therefore, it is necessary to correct the decision above. According to the C4.5 algorithm, the following steps should be taken:

1. Control parameters adjustment:

$$\delta(A) = \frac{77.81{\cdot}1 + 5.05{\cdot}0}{77.81 + 5.05} = 0.94, \tag{11}$$

$$\delta(B) = \frac{13.2{\cdot}1 + 45.71{\cdot}0}{13.2 + 45.71} = 0.22, \tag{12}$$

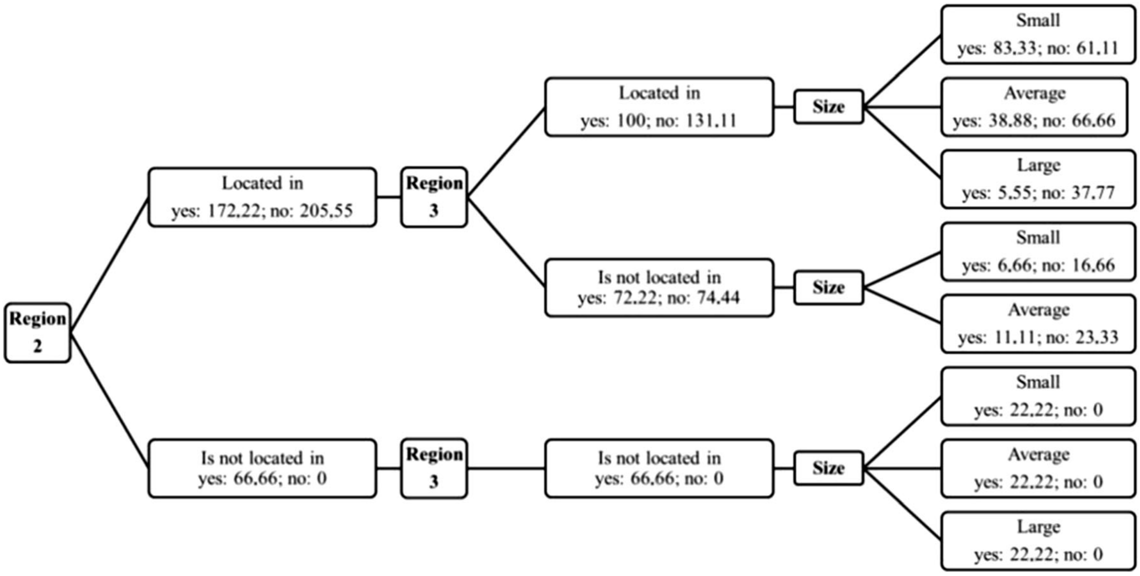


Fig. 9 Path of motion in the decision-making process on the basis of a fuzzy tree structure to evaluate the axial porosity of the continuous cast billet

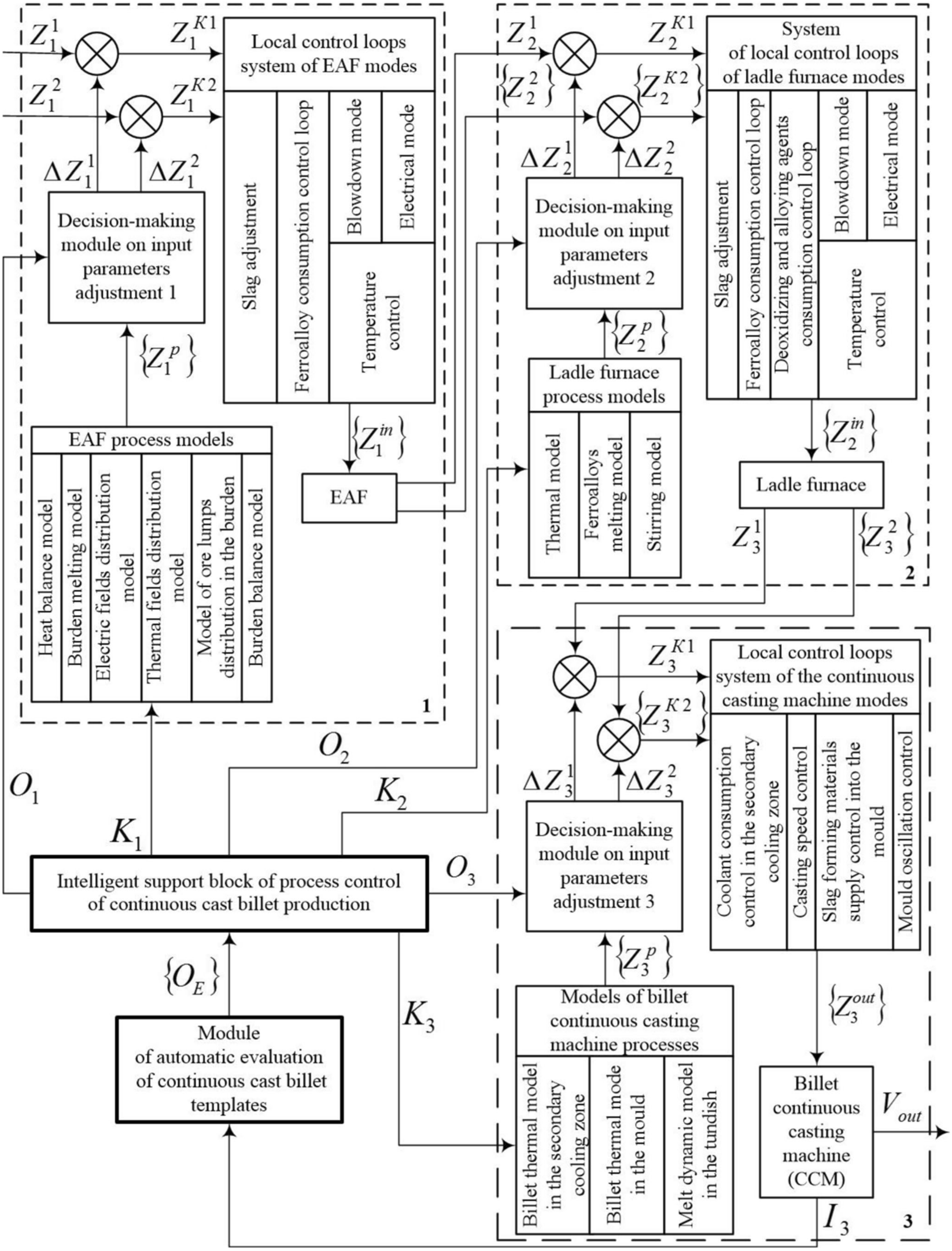


Fig. 10 Structure of the automatic system for intelligent support of continuous cast billet production control

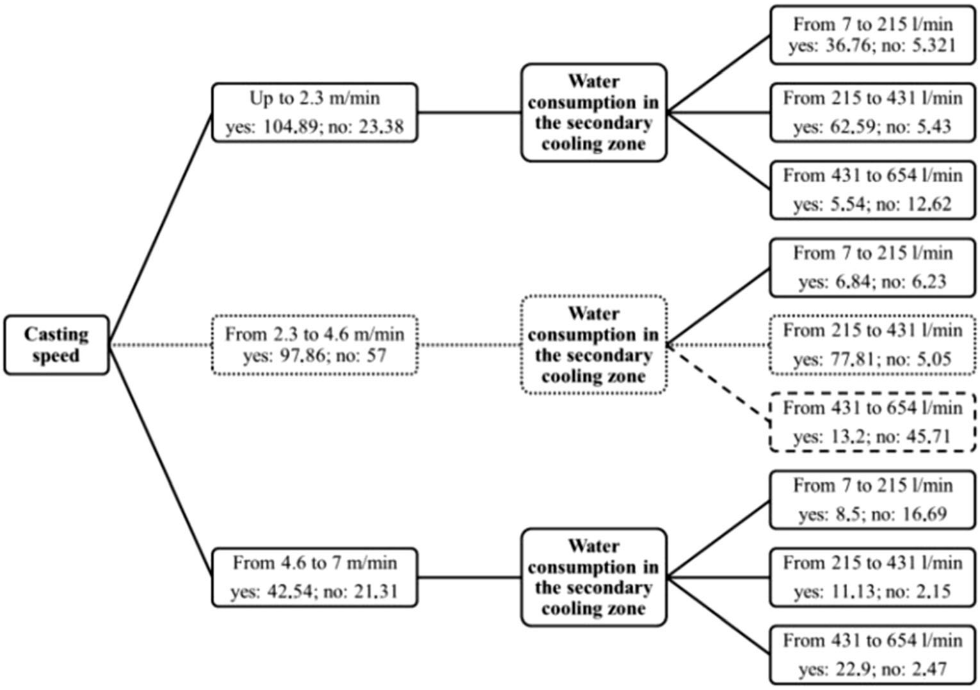
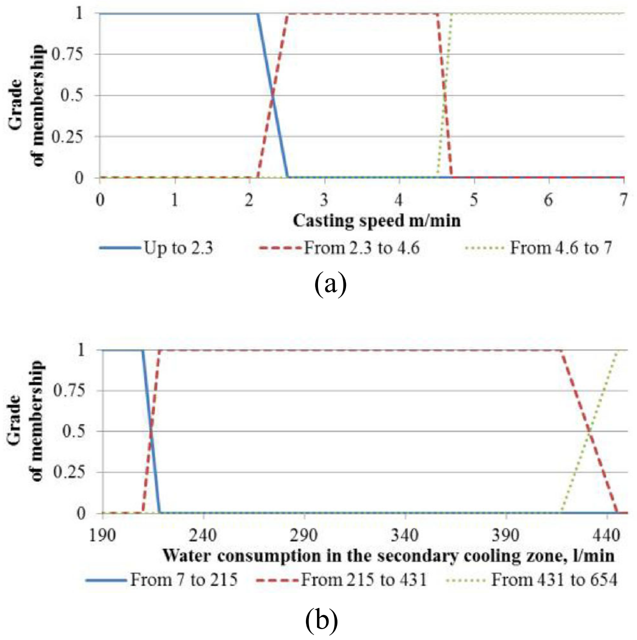


Fig. 11 Part of the motion path in the decision-making process on the basis of the fuzzy tree structure for continuous cast billet quality forecast

where the leaf of branch B has the least influence on the objective function.

2. Selection of "Water consumption in the secondary cooling zone" crosspoint for the branch of the discovered leaf because it has the lowest value of the grade of membership.
3. Determination of the non-zero grade of membership for all subunits of "Water consumption in the secondary cooling zone" crosspoint.



(a)

(b)

Fig. 12 Membership function graph for classification of: **a** steel casting speed; **b** water consumption in the secondary cooling zone

4. Determination of the maximum subunit membership grade for branch A subunit. Water consumption in the secondary cooling zone of 320 l/min should be selected as this decision has a grade of membership in branch A equal to 1.
5. Evaluation of the selected decision:

$$\delta(D_j) = \frac{(77.81 \cdot 1 + 5.05 \cdot 0) \cdot 1}{(77.81 + 5.05) \cdot 1} = 0.94. \tag{13}$$

This decision meets all the requirements necessary for quality billet production.

6. Using binary analysis, it is possible to determine that if water consumption is 438 l/min, the decision has a grade of membership in quality billet class equal to 0.5 corresponding to 2 points.

Thus, reducing water consumption from 444 to 438 l/min improves the billet quality from 2.5 to 2 points. The decision makes use of only two dashed line branches. Decision 0.14 belongs to the upper and 0.86 to the lower branch. For this decision, the produced billet has a grade of membership for a quality billet of 0.357 corresponding to 2.5 points using OST.

The billet is considered to be of good quality if it scores less than 2 points. Therefore, it is necessary to correct the decision. According to the developed algorithm, control parameters are adjusted in the following way: Coolant consumption is reduced from 444 to 438 l/min; thus, billet quality evaluation is reduced to 2 points making it possible to qualify the billet as a quality one.

As the developed tree is adaptive, it can be relearnt in case the technological process changes and it can react to the examples that have not been defined in the tree. This feature makes it possible to change the importance of a parameter after a number of tree adaptations to introduce shorter decision branches, thus reducing the number of parameters to be adjusted.

6 Organizational and technical instructions for implementation of research results

To implement the control action adjustment from the program analyzer module and decision-making block on each machine, it is necessary to:

- Integrate the program analyzer and decision-making block modules into the corporate information system of the enterprise;
- Install the developed system for production processes monitoring into workstations of the EAF operator, ladle furnace operator, billet continuous casting machine operator, the Head of the EAF shop, the Head of dispatch control, heads of laboratories, and plant-operating engineers of the central control laboratory;
- Update the plant-operating engineer workstation by installing a super accurate gesture controller; and
- Train personnel to maintain and operate the installed modules of the program analyzer and decision-making block.

The hardware complexity of the plant-operating engineer workstation requires a PC with a modern CPU that has a processor speed of at least 1.6 GHz and random access memory of at least 1 Gb, a super accurate gesture controller capable of surface image acquisition with a resolution of at least 300 dpi (dots per inch), and the ability to develop a dot cloud with an accuracy of up to 0.01 mm. The decision-making block needs a server with a processor speed of at least 1.6 GHz and four processor cores and random access memory of at least 4 Gb.

The developed automatic system for the intelligent support of continuous cast billet production control made it possible to extend the structure of the monitoring system (Fig. 13). It was proposed to introduce additional dialog boxes to display the history of internal defects development and decisions for contingency prevention.

The following symbols were introduced in Fig. 13: 1 is the information about the values of technical parameters for each production unit obtained from the production site level, 2 is the information about the process state obtained using a human operator in the monitoring system, 3 is the melt produced in the EAF, 4 is the melt produced in the ladle furnace, 5 is a continuous cast billet, 6 is a sample image for quality evaluation, 7 is the information about billet quality, and 8 is the information about current billet quality and the possibility of set point values changing.

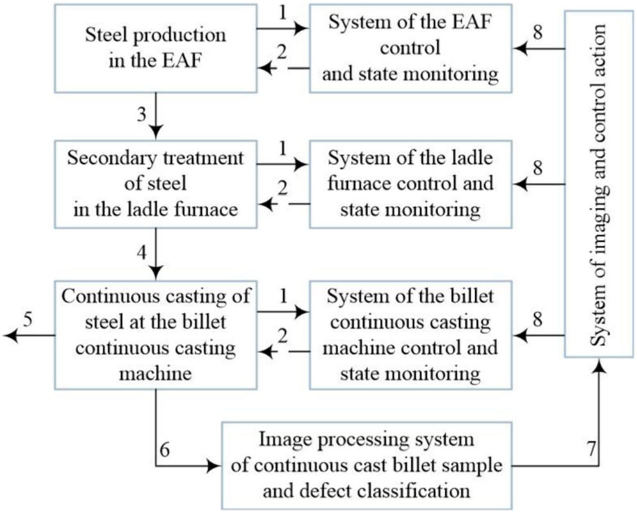


Fig. 13 Development scheme for the billet production process monitoring system

The introduction of the research findings will result in estimated savings of 981,000 rubles per annum from the reduction in inferior quality billets and claims from customers.

7 Conclusions

The following can be concluded on the basis of the research work:

1. Theoretical analysis made it possible to establish the drawbacks of the current system and justify the means chosen for its improvement. Consequently, methods to locate, acquire, and process information for developing the automatic system for intelligent support of continuous cast billet production control making use of information on the quality of the finished product were proposed.
2. Mathematical support was developed for the program analyzer of the continuous cast billet quality for the automatic process control system. The developed program module makes it possible to automatically recognize and classify billet defects, reduce the influence of human factors on billet quality evaluation, and improve the reliability of information used in the automatic process control system when it makes decisions on production process adjustment.
3. Mathematical and software support was developed for the set point adjustment module operating in the automatic system for intelligent support of multistage continuous cast billet production control on the basis of an adaptive fuzzy tree with a dynamic structure. When the developed program module was installed in the operating automatic process control system, it extended the system of

automatic monitoring and control and provided scientifically grounded analysis of factors causing billet defects.

4. Organizational and technical instructions were developed for the operation of the automatic system of intelligent support of multistage continuous cast billet production control module. This included the arrangement of the industrial engineer's workstation, the choice of the hardware platform for the operation of the program analyzer, and the calculation of the estimated savings as a result of the operation of the developed modules. Introduction of the developed solutions into the operating automatic process control system will save up to 981,000 rubles per annum because of the reduction in inferior quality billets.

The program modules were tested at RTC Ausferr, KonsOM SKS, and in the laboratory for physical, mechanical, and metallographic testing of plate and rod steel at OJSC "Magnitogorsk Iron and Steel Works".

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