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On solving problems of operational forecasting of main pipeline weld joint quality

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Introduction. Since welding is the only means to connect pipe lengths into a continuous line when constructing main pipelines, modern quality management systems for the welding industry products are based on minimizing the occurrence of specific defects. This is achieved through monitoring and documenting welding procedures.
Materials and Methods. The analysis of monitoring systems customized for manual, mechanized and automatic orbital welding has shown that the industry urgently needs systems that not only control and document the welding process, but also predict the quality of weld joints. This actualizes the need to develop an intelligent module that could, basing on real-time monitoring results, predict the quality of welded joints on the fly.
Results. Since the theoretical connection between the forecasting results and weld quality attributes is characterized by the interaction of a significant number of physical phenomena continuous in time, the results of welding can be described only by a sufficiently complete nonstationary physicomathematical model of the welding process. However, in order to be able to predict the results of welding directly during the monitoring of the process, a simplified forecasting model is proposed whose key feature is the ability to perform calculations synchronously with the real process, which is implemented in a real-time mode with a given interval.
Discussion and Conclusions. The major obstacle to the successful functioning of the operational forecasting module, apart from the length of the numerical solution of equations, is an estimation error. To ensure the minimum error of virtual display during simplification, it is necessary to conduct comprehensive studies of the significance and influence of individual factors and phenomena on quality attributes. These observations determined the content and sequence of work on the creation and implementation of an intelligent module for the operational forecasting of welding quality. Undoubtedly, the information on the forecasting of the weld joint quality should enter a higher-level pipeline quality management system, as well as be analyzed by construction organizations in order to develop preventive measures to improve the organization and performance of welding work.
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Keywords: welding, quality forecasting, welding procedures, weld joint, main pipeline, physical and mathematical model

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Introduction. The consistent development of the oil and gas industry infrastructure requires continuous improvement of pipeline systems since pipeline transport is currently most preferred for transportation of hydrocarbon raw materials and products of its processing. It is known that at the present stage of technological development of the construction of main pipeline systems, welding is the only way to connect individual pipes into a continuous line on site.

Given the consequences of accidents and failures in operation, trunk pipelines are classified as hazardous production facilities. Since, according to Rostekhnodzor, over 85% of accidents and catastrophes at facilities occur due to depressurization or failure of welded joints, the quality maintenance of welded joints is quite a chellenge. Therefore, the quality of welding is the basis for the safe operation of any pipeline transport system [1].

The quality of the weld is assessed by the dimensions of its cross section, the mechanical properties of the weld metal and the heat-affected zone (HAZ), the distribution of stresses and residual deformations, probability of cold and hot cracks, the presence of pores, non-fusion and other defects. Modern quality management systems for welding products are based on minimizing the probability of specific defects. For this, accident-preventive measures are taken to prepare and implement welding processes. This approach contributes not only to improving the quality of welded joints, but also to improving welding technologies, rational selecting welding materials, and developing methods for monitoring welding processes. In this regard, we consider in more detail the basic welding technologies used in the construction of pipelines.

Materials and Methods. Currently, the most commonly used method of joining pipes of main pipelines into a string is fusion arc welding. In the construction of pipelines, manual, mechanized and automatic welding is used. Manual arc welding is characterized by simplicity of implementation, equipment mobility, but it is quite laborious and requires a large number of qualified personnel. In addition, under manual arc welding, a significant number of defects can occur. Mechanized (semi-automatic) pipe welding, in comparison to manual arc welding, is more productive. However, it is not free from shortcomings, the major of which are increased spatter of electrode metal, problems of gas protection, aerosol emission, especially under FCAW wire welding. It should be noted that the methods of manual and mechanized welding are characterized by a high degree of subjective influence of performers. The "human factor" is less significant for automatic welding methods. However, orbital welding, in comparison to manual and mechanized welding, is less mobile. Currently, among installations for orbital welding, it is required to single out equipment for consumable electrode welding with controlled droplet transfer of electrode metal [2]. To reduce the impact of characteristic disturbances, it is very promising to use adaptive technologies that promptly correct the welding process [3].

Among consumables widely used for automatic and mechanized welding, gas-proof flux-cored wires can be distinguished. FCAW wires, despite a number of advantages, are used in much smaller volumes.

In recent years, attempts have been intensified to introduce more efficient automatic welding technologies under construction, for example, plasma, laser, butt-resistance welding, and also welding with a combination of various heat sources [4]. However, all these welding methods are not yet industrially usable or are used on a very limited basis. The introduction of automatic welding processes reduces the human impact on the quality of weld joints. However, close attention is paid to issues related to the fulfillment of the prescribed requirements and instructions on the work execution by a welder or operator of welding equipment.

Currently, welding monitoring procedures have become an integral part of scientific and technical support for the construction of trunk pipelines. Monitoring procedures provide observation of energy parameters of welding processes, prevention of causes for non-compliance of welded joints with the requirements of standards and technical documentation (STD), and control of their elimination. At the same time, monitoring procedures provide the implementation of a number of requirements for documenting the work performed. This is achieved by connecting special recorders with appropriate software to the modern welding equipment [5].

A typical operation scheme of such systems is shown in Fig. 1.

A number of domestic high-tech science-based enterprises are involved in the development of such systems of monitoring, registration and documentation of the parameters of the welding process. Systems can be integrated into modern digital sources of welding current or manufactured as separate units.

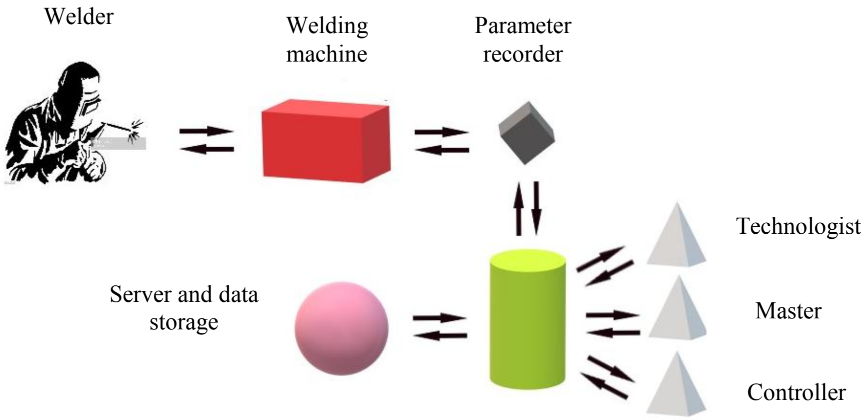

Fig. 1. Information flows of welding process monitoring

When monitoring the process of arc welding for recording parameters, the authors of [6] developed a polyweld (up to 64 welding points) recording system for measuring, displaying and saving data on the welding current, arc voltage and temperature of the weldable workpieces being welded. The registers of such a system can be located at a distance of up to 300m from the installation site of a personal computer with dedicated software.

Similar solutions are used by other developers of welding process documentation systems, for example, “Storm” enterprises, NPF ITS, “Telma”, “Alloy”, and others. The “Weld Telecom” monitoring and control system developed by “Alloy” provides data both from a single point and from a whole stock of welding equipment through a remote server using a wired or wireless Wi-Fi network. Such capabilities of the Weld Telecom system provide monitoring of the operations performed by the welders, and monitoring of the technical condition of the welding equipment. Moreover, the system allows both monitoring the process and transmitting commands for adjusting welding modes, which should be considered a significant step in implementing the Industry 4.0 concept using sensors and networks. In addition, the system provides documentation of welding processes with the automation of the collection, systematization and data storage for the formation of the weldable product certificates and their application in managing product quality. The Weld Telecom system capabilities for processing and visualizing the welding mode parameters are shown in Fig. 2.

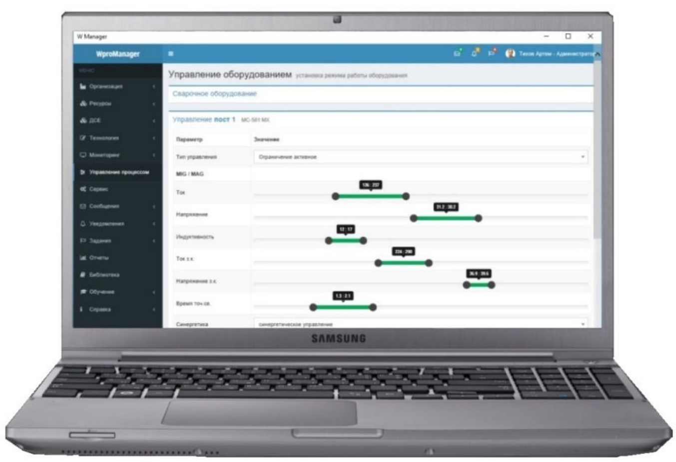

Fig. 2. Weld Telecom system visualization options

Foreign developers and manufacturers of welding equipment are actively involved in the development of systems for registering and documenting welding processes. Fronius (Austria), Kemppi (Finland), Miller Electric (USA) and a number of other foreign companies demonstrate solutions similar to Russian companies for registering welding process parameters.

It should be noted that Production Monitoring systems from Lincoln Electric (USA) and Merkle Quality Control from Merkle Group Inc (USA) have somewhat greater capabilities. These systems not only monitor and record the welding process parameters, but also identify and record data on their deviations [7]. The on-line Production Monitoring system compares the voltage, current, electrode wire feed speed, time interval of the welding process predefined by the user to the actual values. Merkle Quality Control system provides documentation and control of up to 8 parameters of the mechanized welding process with the possibility of archiving. Such capabilities of the deviation fixation system are provided by independent sensors of current, voltage, wire and gas. However, such systems work stably only with the proprietary equipment.

Therefore, it can be stated that the most popular systems for monitoring welding processes are used to document their parameters, as well as to analyze the consumption of materials, use uptime, register the out-of-tolerance condition, and discipline welders. However, none of the systems answers the key question – what consequences will the identified deviations lead to. Given the entry, we need systems that not only control and document the welding process, but also predict its results. Based on the foregoing, we need systems that could not only control and document the welding process, but also predict its results. Despite the attempts to predict the weld joints operational quality according to the monitoring results of the welding process parameters undertaken both earlier this century [8] and later [9], no forecasting systems on site exist to this date. All this actualizes the need to develop an intelligent module that can quickly predict the quality of weld joints. However, such a module can only be created through linking the quality indicators of welded joints with the actual parameters of the welding mode recorded in the on-line mode.

Discussion and Conclusions. Unfortunately, the theoretical relationship between the forecasting results and weld quality indicators is characterized by the interaction of a significant number of physical phenomena that are continuous in time since they determine the heat supply, the conditions for the formation and crystallization of the weld pool, the dimensions of the weld and the HAZ microstructure [10]. However, the representation of welding processes in the form of complex, multifactor systems provides using mathematical modeling under their study. It is easier to collect the data required for forecasting under stationary shop-floor conditions [11]. However, under the conditions of the route, it is difficult to measure a number of the manual and mechanized welding parameters. For example, movements of a welder's hand and parameters of the electrode oscillations in cutting under manual or mechanized welding are uncontrollable values. They can be judged only by indirect signs.

The impact of the joint assembly on the quality of the weld formation should be considered, since even the assembled joints accepted by the Quality Control Dept (QCD) will have deviations within tolerance. If under orbital welding, scanning laser-television systems can be used to determine the real profile of welded edges [12], then it is rather difficult to use them for manual and mechanized welding. Therefore, predicting the quality of manual and mechanized welding only by the results of processing the actual values of the process energy parameters can only be approximate, just a matter of judgment. To increase the reliability of such a forecast, real data on the distribution of grooving sizes along the pipe joint are required. In cases where it is impossible to use laser-television scanning, other approaches should be used. Thus, if we neglect the change in the gap under welding due to thermal expansion and deformation of the metal, then monitoring the joint assembly under welding can be replaced by measuring its dimensions before welding starts. Since the gap size varies relatively slowly along the joint, it is sufficient to measure at several points, and determine the remaining dimensions of the joint through interpolating the available results. There is another possibility of increasing the reliability of the forecast when it is difficult to consider welding parameters. Their possible spread (for example, wire diameter tolerance, possible variations in welding and wire feed speeds, joint clearance, etc.) can be taken into account. However, in this case, it is rather difficult to impose deviations from the instability of those parameters that are not measured on the simulation result.

It should be noted that due to fluctuations in the welding process parameters, the quality indicators of welds are unevenly distributed both along the length and thickness of the welded joint. Therefore, the final task of the module for predicting the quality of joints is to identify precisely those sections of the weld where the deterioration probability of quality indicators is critically high. Obviously, such a complex relationship of quality indicators and the results obtained requires using modern forecasting tools.

With this in mind, the predicted results can only be described by a dynamic (non-stationary) physicomathematical model. Considering the problems of fixing an extended set of parameters, surrogate optimization techniques should be used in the model [13]. Given these considerations, Fig. 3 shows the structure of the dynamic physical and mathematical model used as part of the operational forecasting module for the quality of weld joints by the minimum number of analyzed parameters.

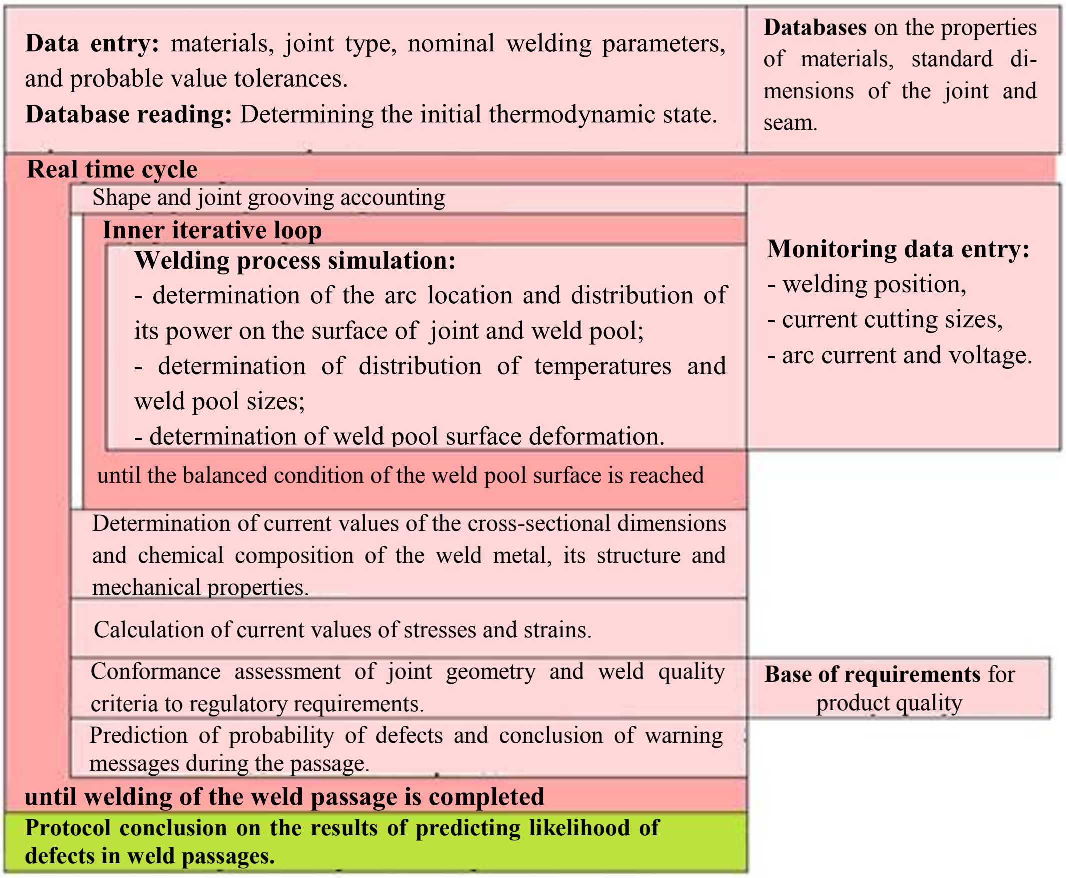

Fig. 3. Structure of physicomathematical model for predicting welding process results as part of intelligent module

Before welding, information on the process is input into the program: the type of connection and the form of cutting, the thickness of the weldable parts, the grade of steel, the grade and diameter of the electrode wire, shielding gas, and the recommended welding modes. Then, this information is given in the certificates for welded joints, which also contains data on the joint number, the serial number of the welding equipment, the name of the welder, the start and end times of the joint welding process.

A unique feature of the model for performing a quality forecast under welding is the need for synchronization with the real process of calculations, which is implemented in a real-time cycle with a given step determined by the weld pool response time. Therefore, it should be less than the length of the change in the depth of the crater on the surface of the bath when the arc current changes. The modeling of the thermodynamic state of the joint should be carried out at each step of the real time cycle since a major feature of arc welding, in addition to the possibility of the arc penetration into the crater of the weld pool, is its volume variation. With this in mind, the energy and mass balance should be achieved in a time not exceeding the selected step. The thermodynamic state of the metal makes it easy to determine the size of the weld pool, the thermal welding cycle, and the chemical composition of the weld, which enables to calculate the number of structural components and evaluate the mechanical properties of the weld metal and HAZ. In addition, using the known methods [14], stresses and strains in the vicinity of the weld pool can be calculated.

Such solutions provide to evaluate not only the possibility of hot cracking, but also the tendency of the weld metal and HAZ to cold cracking according to the results of calculating the amount of martensite.

Embedding a physicomathematical model in the computer program of the operational forecasting module allows you to evaluate the probability of defects directly under welding (Fig. 4).

For reliability of the results, it is required for the speed of virtual reproduction of the process to be greater than its real course. Therefore, the major obstacle to the successful functioning of the operational forecasting module is the duration of the numerical solution to the equations of the physicomathematical model. This circumstance forces us to simplify both the model itself and its numerical implementation. The model simplification can be achieved through limiting the scope of its application (specialization), as well as through reducing the number of measured parameters and determined quality indicators. However, to reduce the error of virtual reproduction under such simplification, it is necessary to conduct comprehensive studies to assess impact of individual factors and phenomena on the quality indicators of welded joints.

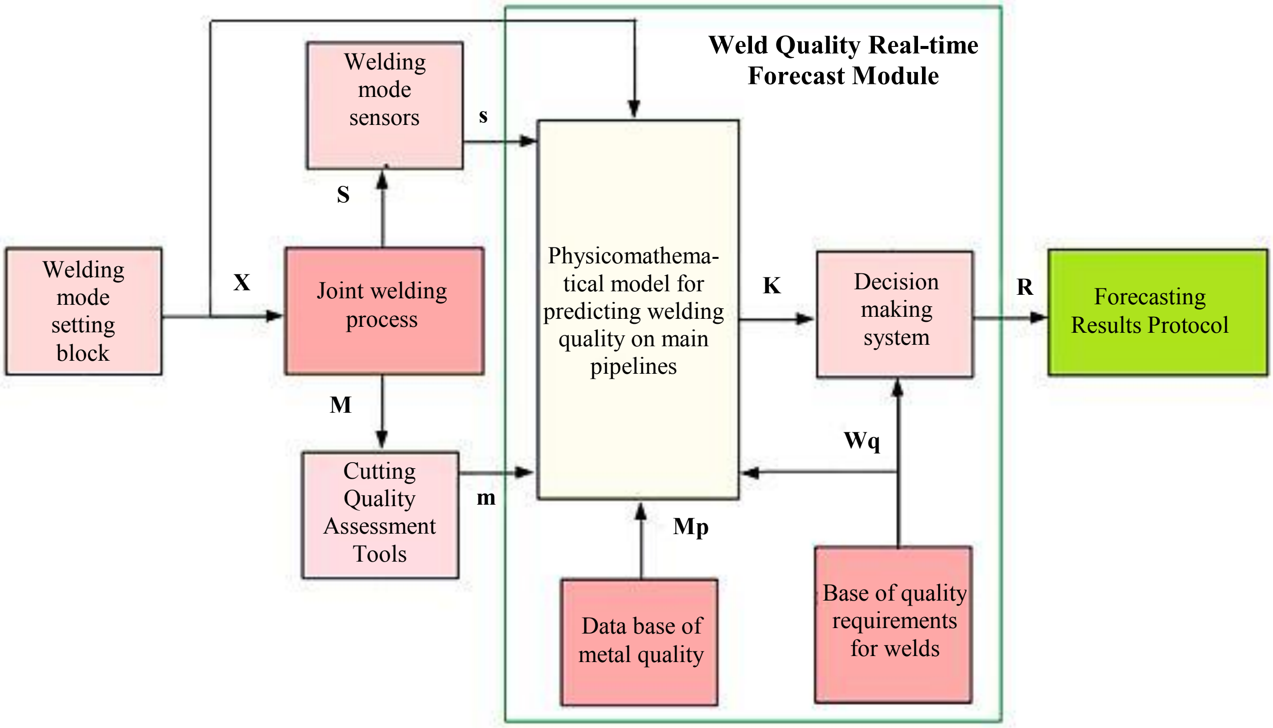

Fig. 4. Structure of system for predicting welding results:
X are set parameters of welding process; S are controlled parameters of welding process; s are measurement results of welding parameters; M is data on joint geometry, cutting quality and spatial position; m are measurement results; Mp is data on physical properties of welded metal; Wq is regulatory data on quality requirements for weld; Sp is comparison base of mode parameters; K is information flow; R is signal of results of comparison of weld quality to regulatory requirements

It stands to reason that the structure of the intelligent module for predicting the welding process results, its software will be specified and revised according to the results of pilot industrial use under the real-time forecasting of the quality of welded joints directly during welding work.

The desired sequence of work on the creation and implementation of an intelligent module for real-time forecasting of welding quality and the sequence of their implementation are presented in Fig. 5.

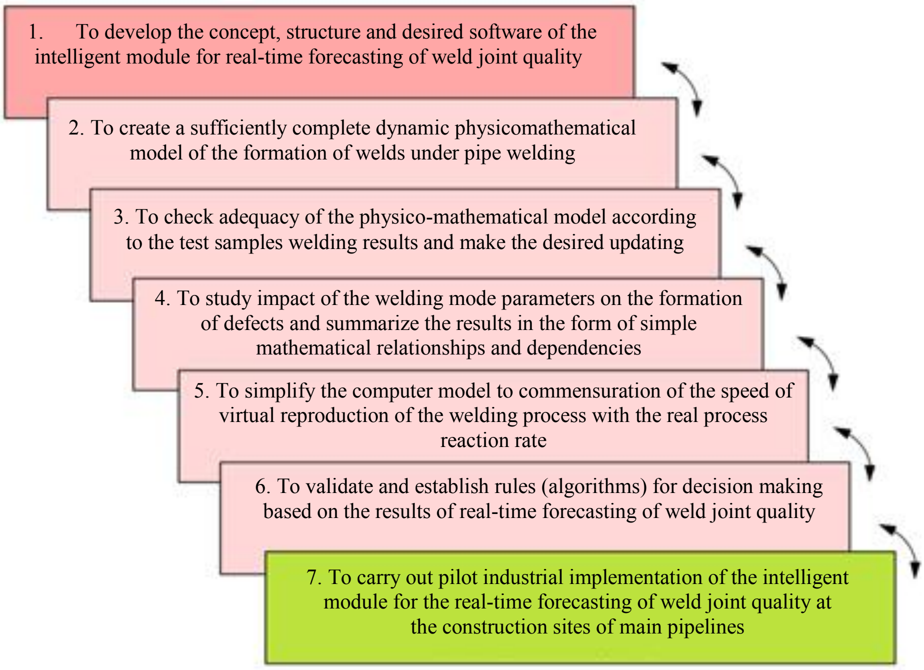

Fig. 5. Content and operating sequence on creation and implementation of an intelligent module for real-time forecasting of welding quality

To diagnose the technical condition of the main pipelines, it is required to collect all available information about the facility. To do this, information on predicting the quality of welded joints should go to a higher-level pipeline quality management system, for example, to an integrated diagnostic monitoring system for the linear part of main gas pipelines [15], or to a system for information analysis on the state of oil pipeline components [16, 17]. Construction organizations need information not only about defects in welded joints, but also about the causes of their occurrence. Therefore, data on the real-time forecasting of the quality of welded joints should be analyzed by construction organizations to develop preventive measures to improve the organization and performance of welding operations. It is advisable to carry out such an analysis under stationary conditions, with the inclusion of a more complete computer model of the welding process and an information storage device with appropriate filters in the structure of the forecasting module. However, this approach also requires additional study on the significance of individual factors and phenomena by quality indicators. Only then will the information on real-time forecasting the quality of welded joints become a truly efficient tool for taking preventive measures and removing the causes of defects.

Conclusions

1. A method is proposed for processing data for monitoring the welding process using a deterministic physicomathematical model that provides a sufficiently accurate prediction of the welded joints quality directly during welding, based on the relationships between the mode parameters and specified quality indicators of the joints.

2. Real-time forecasting is provided by a special intelligent module whose software includes a computer program for the implementation of a physicomathematical model of online forecasting of the quality of welded joints.

3. Since the major obstacle to the application of the proposed method of online data processing is high requirements for the speed of solving the model equations, then, to provide a high speed of virtual reproduction of the welding process, it is proposed to conduct comprehensive studies of the significance of individual factors and phenomena on quality indicators. These considerations determined the content and sequence of work on the creation and implementation of an intelligent module for the online forecasting of welding quality.

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Claimed contributorship

A. E. Filyakov: setting the research objective and tasks; literature analysis; text preparation; formulation of conclusions. M. A. Sholokhov: academic advising; the text revision; correction of the conclusions.

All authors have read and approved the final manuscript.