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OPERATIONAL CONTROL AS A MEANS OF WELDED JOINT QUALITY EVALUATION FOR FLASH-BUTT WELDING OF MODERN HIGH-STRENGTH STEELS

Introduction. *Flash-butt welding (FBW) of rails is controlled in real time based on the tolerances of the main process parameters according to the data of specifications. The operational control algorithm enables real-time detection of low quality weld and inadmissible trends in the process.*

Problem Statement. *In addition to the existing method, in order to control the compliance of welding of new high-strength steel rails with the specifications, it is necessary to take into account the width of the heat-affected zone (HAZ). The known numerical methods for calculating the HAZ in real time cannot be implemented because of insufficient computatio¬nal capabilities of modern control systems.*

Purpose. *To develop an algorithm for real-time monitoring of FBW with predicting the width of the HAZ, in compliance with technical specifications.*

Materials and Methods. *A numerical method for calculating thermal fields during flash-butt welding, a regression analysis for HAZ prediction. The HAZ width is calculated based on the process parameters at the burning-off stage and on the upsetting.*

Results. *A real-time algorithm has been developed for controlling FBW of modern high-strength steels with prediction of the HAZ width. The algorithm is based on mathematical modeling of joints formation during flash-butt welding.*

Conclusions. *The regression equation in the form of a second-order polynomial or MLP neural network with a structure of 3 neurons in the input layer — 2 neurons in the hidden layer — 1 neuron in the output layer can be used for calculating the HAZ width in real time with the required accuracy for practical use. Prediction of the HAZ width during operational control expands the possibilities of its use for resistance butt-welding of high-strength rails. The developed algorithm has increased the accuracy and reliability of operational control of FBW in real time.*

Keywords: flash-butt welding, high-strength rails, heat-affected zone, regression model, fuzzy logic, and Sugeno classifier.

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In various industries, the mass production of welded structures successfully applies the flash butt welding technology developed in the Paton EWI. It is based on a software modification of the basic parameters, while using feedbacks to adjust (to stabilize) their instantaneous values.

Fig. 1 shows a typical record of the main parameters: voltage *U* and current *I* at the input of the welding transformer, velocity *V* and shortening of the welding rails *S*, using resistance welding machines designed at the Paton EIW, at the enterprises of *Ukrzaliznytsia*.

As a result of multifactor parameter control, the automatic control system ensures that the requirements for obtaining weld quality indicators according to the specifications (TU) are met [1]. TU data have been obtained from weld studies, including numerous static mechanical bending tests. The set and measured parameter values are recorded in the form of an electronic protocol that is given to operator for information in the course of welding and is transmitted to the *Ukrzaliznytsia* diagnostic center for statistical processing [1, 2]. In the case of unacceptable deviations of the basic parameters from the values specified by the program, the system issues an indication of termination of operation and provides recommendations for eliminating the deviations..

The main disadvantages of existing operational control (regardless of distribution of measured values within the tolerance, "blurring" of the tolerance limits, significance of the effect of individual parameters and their combination on the weld quality) can, to some extent, be eliminated in the control algorithm based on fuzzy logic [1—3].

In recent years, because of necessity to develop FBW technologies for modern high-strength rails, eutectoid rails and increasing requirements for the weld quality, the international standard that governs the requirements for welded joints of such rails [4—7] has introduced additional requirements that limit the allowable changes in the hardness of the heat-affected zone (HAZ) of the welded joint and its width. They are hardly controlled in production conditions. It is possible only while testing the inspection batches of rails.

The purpose of this research is to develop an algorithm of real-time control of compliance with TU for FBW with the prediction of the HAZ width and increase in the accuracy and reliability of real-time control while making butt welding of rails. Known methods of numerical calculation of the thermal field while heating by the finite difference method, which could be used to calculate the thermal field when welding rails, are not suitable for real-time application insofar as they require control systems having a very high currently unreachable computing performance. Statistical regression dependencies of different types, including neural networks, are much easier to imple-

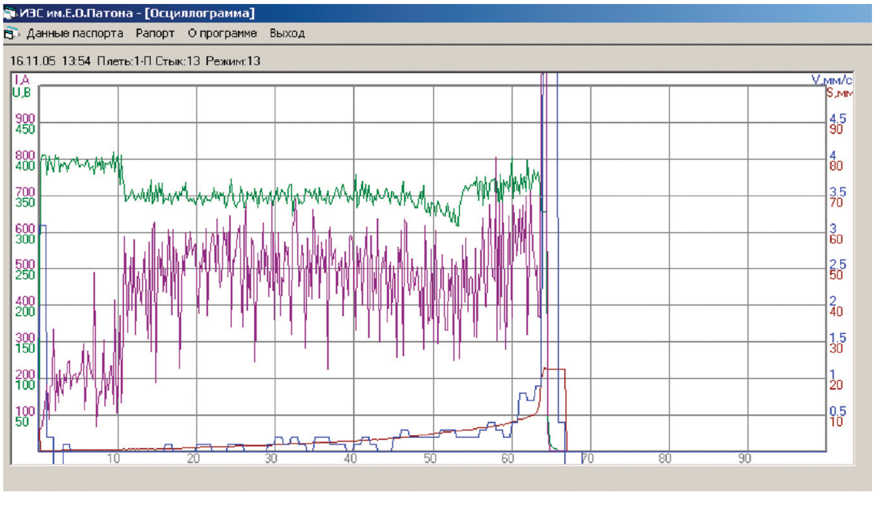


Fig. 1. Oscillogram of FBW parameters: voltage *U* and current *I* at the input of AC transformer-type welder, velocity *V* and shortening *S* of welded parts

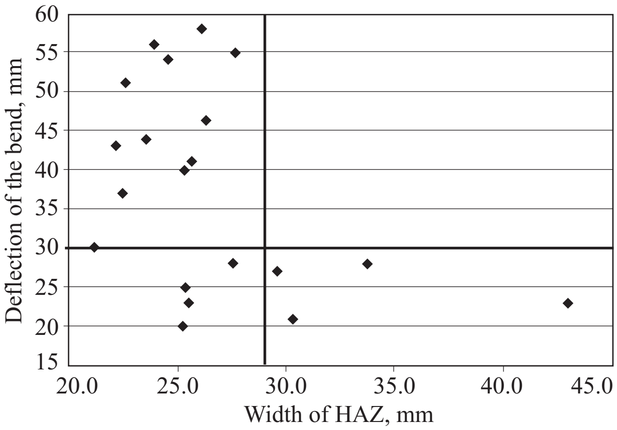


Fig. 2. Dependence of deflection in static bending tests L_{df} (mm) (y-coordinate) on HAZ width as calculated based on welding parameters, regardless slump tolerance (x-coordinate) for K76F steel rails (mm). The red horizontal line is drawn at the level of minimum permissible bend (30 mm), the vertical line corresponds to the level of maximum permissible width of HAZ (27 mm)

ment. However, to build them, it is necessary to have experimental data that satisfy the condition of representativeness [5], in particular, uniform coverage of the entire possible area of the process existence, taking into account the welding results, that is, the number of points with positive and negative results shall be balanced. In practice, these conditions are very difficult to meet because the cost of experiments is quite high, and the production data for welding the samples is usually concentrated in the narrow range with the positive results being more numerous than the negative ones.

To obtain an array of representative data, a mathematical model of temperature field kinetics with continuous melting was used, taking into account the multifactor influence of rapid formation and destruction of single contacts on the heating intensity during the technological cycle of contact welding of railway rails. The model was adjusted, tested, and refined according to the experimental data when heating by the method of melting the rail samples (type P65, grades M76 and K76F) on a mobile welding machine. The heating temperature in the experiments was controlled by thermocouples installed at a different distance from the welding edge along the rail. The calculated arrays balance the number of evaluations for the process that matches and the one that does not match TU. The calculations were made for different types of steels, including K76F converter thermo-strengthened rail steel. Given that the permissible range for the HAZ width when welding rails, according to EU standard [4], is 20—45 mm and the upsetting allowance usually is up to 12 mm, calculations have been made for the HAZ width of up to 60 mm. At this stage, the HAZ width is distance from the metal heated to 500 ° C (isotherm) to the edge along the rail. In the calculations, current and voltage at the input of AC transformer-type welder varied within the range of 200—700 A and 300—420 V, respectively. The control parameters were the value of S_o and the rate of V_o of the shortening of the parts during melting, the electric energy during the melting Q_o, and the parameters for estimating the temperature field (HAZ width without slump), the distance between the point of heating up to 500 ° C and the edge.

While modeling, voltage and welding current were considered not to directly affect the heating temperature, so they were taken into account in energy Q_o. Therefore, these parameters were not used as input data.

The regression models have been calculated for HAZ width using parameters S_o, V_o, and Q_o in the form of first- and second-order polynomials, the simplest multilayer perceptron (MLP) neural networks (structure 3-2-1: 3 neurons in the input layer — 2 neurons in the hidden layer — 1 neuron in the output layer), radial basic functions (RBF) with structure 3-10-1, and adaptive fuzzy neural networks with clustering (subtractive, SBT, and fuzzy c-mean, FCM). In the last two algorithms, the architecture and membership functions were almost identical and differed in the way the clusters were allocated (three clusters in each algorithm) [3, 5]. In all cases, the sum of error squares was used as error function.

Based on the obtained data, the most accurate are fuzzy models with subtractive clustering (standard deviation $S = 0.50$ mm, average relative error $\varepsilon_{cp} = 1.01$ %). The second accurate are MLP neural networks ($S = 0.55$ мм, $\varepsilon_{cp} = 1.16$ %) and regression dependences in the form of incomplete second-order polynomial ($S = 0.56$ mm, $\varepsilon_{cp} = 1.23$ %). The calculations are made for the simplest possible algorithms (relationship) of these models. Complicating them, better results can be achieved. However, this complication can only be effective for a particular dataset. Models with a simpler structure are less sensitive to the replication error that is inherent in experiments. The condition of filtering or low sensitivity to this error is very important for the practical use of the models. If the complexity of algorithm is evaluated by the number of calculated parameters, the best of them are the regression equation in the form of an incomplete second-order polynomial and the MLP neural networks.

Having compared the HAZ values calculated from the welding parameters (regardless of slump allowance) for the rail samples made of K76F steel with the deflection in their mechanical tests, the tolerance for the HAZ width of these rails is shown to have to down to 27 mm, contrary to standard [4] (Fig. 2).

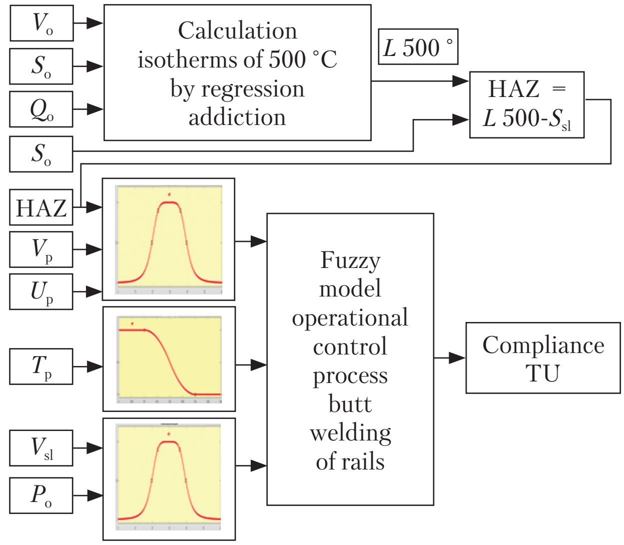
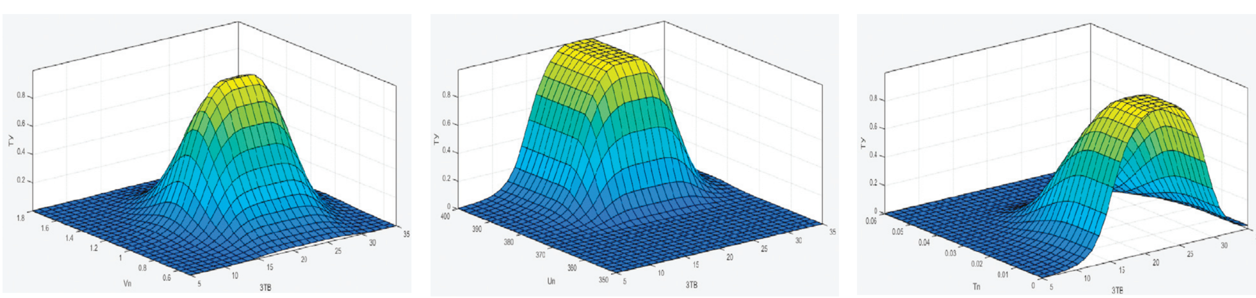


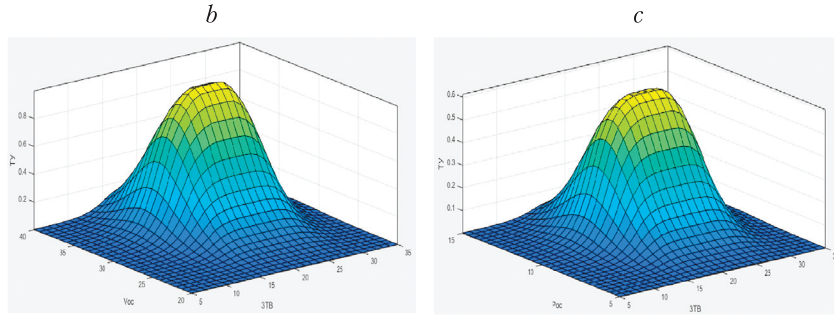
Fig. 3. Flowchart of algorithm for real-time control over compliance with TU for FBW

Taking into account the developed model for the calculation of HAZ width, the following algorithm (Figs. 3, 4) has been selected on the basis of the well-known fuzzy logic operational control algorithm [1, 2].

In addition to S_o, V_o, Q_o, the input parameters of the algorithm are also voltage U_p shortening rate V_p, and duration of the short-circuit current



a *b* *c*



d *e*

Fig. 4. Dependence of compliance with TU on HAZ V_p (*a*), U_p (*b*), T_p (*c*), V_{sl} (*d*) and P_{sl} (*e*) for P65 rails made of K76f steel, using the algorithm shown in Fig. 3. The yellow marks probability >0.9, the blue corresponds to probability <0.2

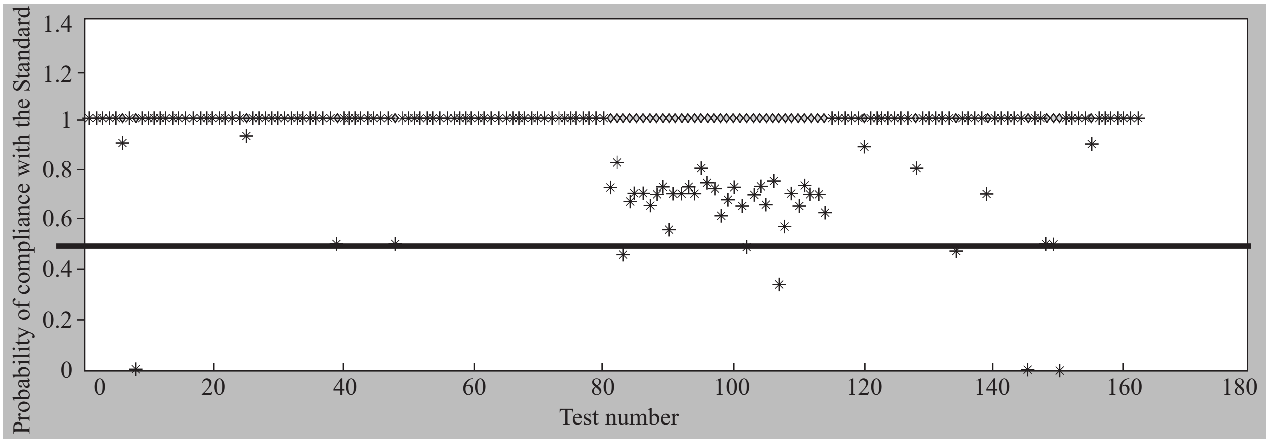


Fig. 5. Evaluation of probability of compliance with TU for FBW (y-coordinate) based on archive data for 162 welds (x-coordinate counts the test number): ◊ — experiment, ∗ — calculations

T_p at the stage of increasing the shortening rate before slump, as well as slump rate V_{sl} and pressure P_{sl}.

The algorithm uses both basic identification methods: the classification (attributing an object based on a set of parameters to one of the predefined classes, in our case according to specifications) or the regression (the result of calculations is an infinite set of classes, and the set of real numbers are HAZ width values).

The proposed system was designed as a fuzzy classifier in the form of the Sugeno system, in which the initial indicator "Compliance with TU" is assigned with "1", in the case of compliance, based on the experiment data, and with "0", in the case of incompliance [7]. It is obvious that the developed algorithm can be adjusted according to the periodic mechanical tests of the samples, the welding of which is obligatory with a period of, at least, half work shift time. The numerical value of HAZ width in natural units is formed at the output of computing module, which can be compared with the test measurements and used to refine the regression dependence.

The described algorithm has been verified using the archive data for butt welding of P65 rails made of M76 and K76F steel manufactured by PJSC MK Azovstal (Ukraine), at rail-welding enterprises of Ukraine. The assessment of compliance with TU has shown the discrepancy with control data only in 5 cases out of 162. In 6 cases, the result is ambiguous because the calculation shows a compliance probability of about 0.5 (Fig. 5). In general, the obtained results may be considered satisfactory.

Thus, in order to calculate the real-time HAZ width with the accuracy required for practical application, it is possible to use regression dependence in the form of second-order polynomial or MLP neural network with the structure: 3 neurons in the input layer — 2 neurons in the hidden layer — 1 neuron in the output layer.

The prediction of the HAZ width as part of operational control extends its use for flash-butt welding of high-strength steel rails. The developed algorithm has made it possible to increase the accuracy and reliability of the operational control of contact butt welding in real time.

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ОПЕРАЦІЙНИЙ КОНТРОЛЬ ЯК ЗАСІБ ОЦІНКИ ЯКОСТІ ЗВАРНИХ З'ЄДНАНЬ ПРИ КОНТАКТНОМУ СТИКОВОМУ ЗВАРЮВАННІ СУЧАСНИХ ВИСОКОМІЦНИХ СТАЛЕЙ МЕТОДОМ ОПЛАВЛЕННЯ

Вступ. Контактне стикове зварювання оплавленням (КСЗО) рейок в реальному часі контролюється за допусками на основні параметри процесу згідно з даними, закладеними в технічні умови (ТУ). Використовуваний алгоритм операційного контролю дозволяє своєчасно виявляти неякісні з'єднання і неприпустимі тенденції в процесі.

Проблематика. Для контролю відповідності ТУ зварювання рейок з нових високоміцних сталей, додатково до діючої методики, необхідно враховувати ширину зони термічного впливу (ЗТВ) при їхньому нагріванні. Наявні чисельні методи розрахунку ЗТВ в реальному часі не можуть бути реалізовані через недостатні обчислювальні можливості сучасних систем управління.

Мета. Розробити відповідний технічним умовам алгоритм контролю в реальному часі КСЗО з прогнозуванням ширини ЗТВ.

Матеріали й методи. Чисельний метод розрахунку теплових полів при стиковому зварюванні; регресійний аналіз для прогнозування ЗТВ. Розрахунок ширини ЗТВ виконано за даними параметрів процесу на етапі оплавлення і за величиною осадки.

Результати. Розроблено алгоритм контролю КСЗО в реальному часі для сучасних високоміцних сталей з прогнозування ширини ЗТВ, в основу якого покладено математичне моделювання процесу формування з'єднань при контактному зварюванні. Алгоритм контролю відповідності КСЗО ТУ подано у вигляді «нечіткого» класифікатора Сугено, вхідними величинами якого є розрахункова ширина ЗТВ, параметри процесу при підвищенні швидкості укорочення рейок перед осадкою та під час неї.

Висновки. Для розрахунку ширини ЗТВ в реальному часі з необхідною для практичного застосування точністю можна використовувати регресійну залежність у вигляді полінома другого порядку або MLP нейронної мережі зі структурою: три вхідних нейрона, два в прихованому шарі і один на виході. Прогнозування ширини ЗТВ при операційному контролі розширює можливості його застосування для контактного стикового зварювання високоміцних рейок. Розроблений алгоритм дозволив збільшити точність і надійність операційного контролю КСЗО в реальному часі.

Ключові слова: контактне стикове зварювання, високоміцні рейки, зона термічного впливу, регресійна модель, нечітка логіка, класифікатор Сугено.