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Optimization of the Mode of Contact Butt Welding of Railway Rails

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Abstract—Optimization of the technological process for manufacturing of long-length rail lashes is a difficult problem since in addition to a large number of operations, the equipment used today for contact butt welding of railway rails by pulsation reflow has many technological parameters (input factors) that affect the quality of the resulting welded joint (output factors). So many parameters do not allow one to select the full the optimal welding modes and leads to the impossibility to use a complete or fractional factorial experiment. In the work, the data of 79 experimental welding was processed by the regression analysis. The main stages of a welding process are identified: the first stage of melting; the second stage of melting; forcing; and precipitation. Based on the obtained oscillograms of the welding process using a K1100 rail welding machine when welding rails of the R65 type of the DT350 category, we have determined the average values of current, voltage, movement speed of the movable frame at various stages of melting, as well as precipitation force, precipitation time under current, and precipitation paths at the last stage. The obtained regression equations that determine the results of tests for static three-point bending were analyzed, and unsatisfactory parameters with respect to Student's *t*-criterion were eliminated from them. The finally obtained regression equations consider the influence of each technological stage of the contact butt welding of railway rails on the output properties and the model is adequate according to Fisher's F-criterion. Using these regression models, the recommended modes of contact butt welding by pulsation reflow were obtained and tested at a rail welding company.

Keywords: contact butt welding, rail steel, spark gap, current strength, melting stages, regression equation

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INTRODUCTION

Railways provide transportation of goods and passengers in large volumes and over long distances, at the same time, the total volume of traffic and the freight density are growing every year. All this leads to the need to build new and repair old railway tracks [1–3].

In this case, the main load falls on the rails, and the rail joints are the weakest point of the track since an additional dynamic effect of wheel on the rail occurs in them. The main way to reduce this impact for a long time is to increase the length of rails with a decrease in the number of joints [4, 5].

Currently, the progressive design of the railway track is a jointless track, which allows one to build high-speed railway lines in the absence of rail joints using advanced resource-saving technologies for the construction and maintenance of the railway track. The most effective method of joining rails into a jointless track in the terms of technical and economic indicators is the electric contact welding. The method of pulsation reflow is currently used, which allows one to select the optimal thermal cycle for welding rails depending on the chemical steel composition. At the same time, there are difficulties for welding of high-carbon steel, which is the material of rails, such as the need for heat treatment after welding to obtain standard mechanical properties and the variability of mechanical properties from welding to welding. In this case, the defects in the welded joint occupy 35% of all the defect types. Currently, at rail welding enterprises, the quality indicator of welding is the results of continuous ultrasonic testing of welded joints as well as the results of mechanical tests of samples of welded rails for three-point bending with obtaining the values of the bending force and the sag [6, 7]. Therefore, it is important to analyze a change in the mechanical properties of the joints depending on the change in the technological parameters of welding as well as to optimize the welding parameters to improve the quality of welded rail joints.

The aim of this work is to improve the quality of welded joints of differentially hardened railway rails welded by the electric contact method by means of optimization of technological parameters.

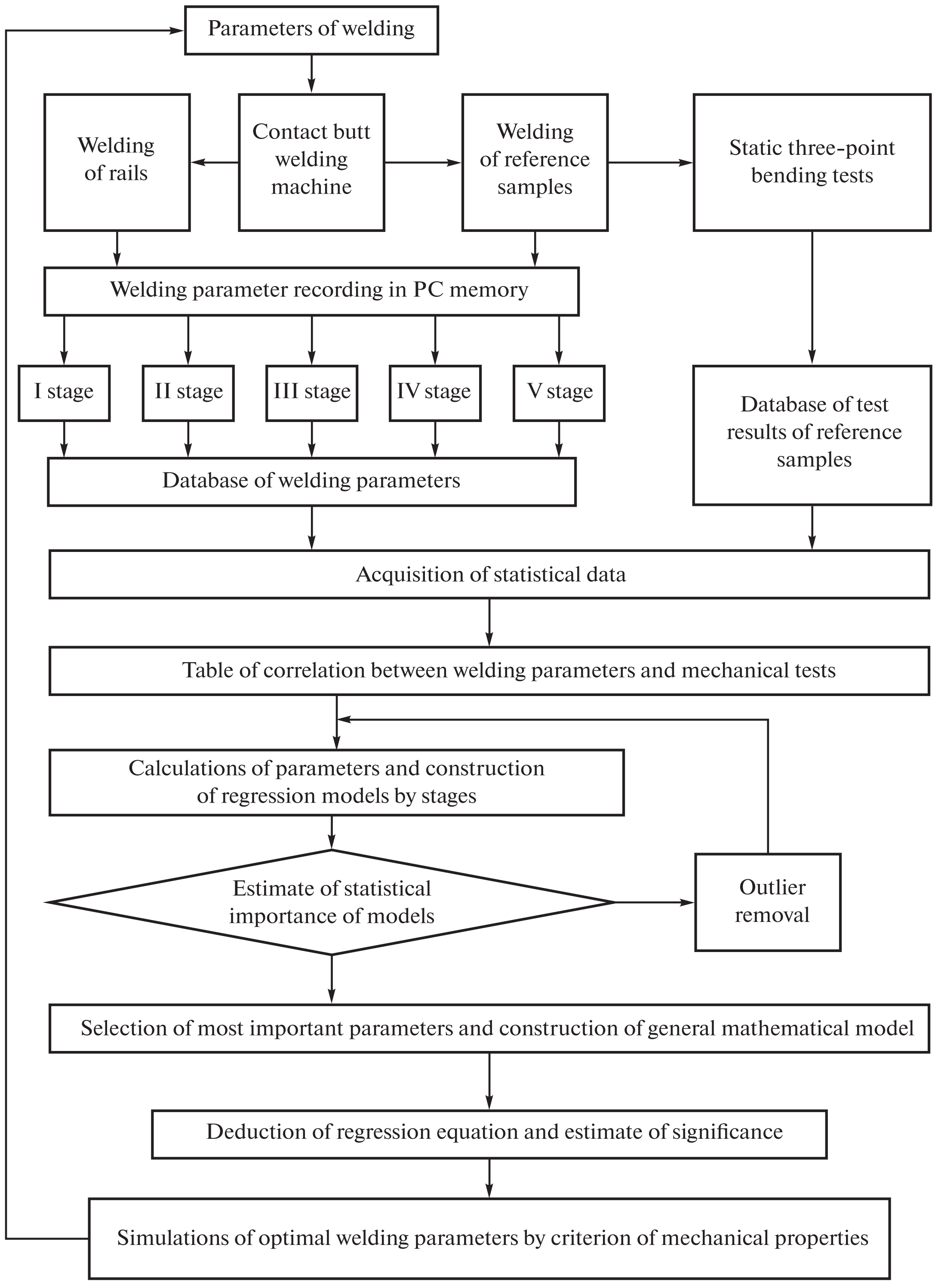

Fig. 1. Research algorithm.

MATERIAL AND METHODS OF STUDY

The optimization of the parameters was carried out according to the algorithm presented in Fig. 1. The optimization consisted of the following stages:

— data collection for five stages of welding;

— correlation analysis;

— calculations of parameters and construction of regression models for each stage of rail welding (10 equations for each machine based on the output parameters (bending force and sag));

Table 1. Ranges of welding parameters for a rail-welding machine

Name of stage	Ranges of welding parameters					
	T, s	I, A	U, V	P, atm	V, mm/s	S, mm
I stage of melting	28–46	7–1088	335–440	27–42	0.00–0.67	4.4–5.4
II stage of melting	60–100	24–736	148–424	26–35	0.22–0.89	7.0
Forcing	4.2–6.1	110–788	280–443	27–33	1.33–1.89	6.5
Precipitation	1.1–3.0	6–1174	2–423	25–129	1.56–9.33	17.8–18.6
Burr removal	1.0	2–324	1–105	71–129	0.11–0.56	0.1–1.0

— clarification of statistical significance, i.e., suitability of the model for use in order to predict response values;

— identification of outliers and their removal;

— selection of the most significant factors with their further inclusion in the overall model;

— substitution into the model of the optimal parameters based on the signs of the regression equation and approbation of the obtained mode [8–10].

To optimize the process of contact butt welding of rails [11, 12] by pulsation reflow using K1100 machines at a rail welding enterprise, the regression analysis of production control data of rail welding and tests of rail specimens for static bending was used [13–15]. The data collection was carried out in two stages. First, the rail welding and static transverse bending data were collected for three K1100 machines for two months. At the second stage, after finding the optimal parameters for three machines, the welding and testing data were collected for a single K1100 machine [16–18].

The production data were processed using the Statistica 10.0 software package. One of its important properties is the operation speed for a large amount of data and the processing power of applications that require regular database queries and complex data management. The software package also includes a graphical module that contains convenient tools for data visualization and graphical analysis [19, 20].

RESULTS AND DISCUSSION

79 joints were welded using a K1100 machine and they were subsequently tested for static three-point bending. The ranges of controlled parameters are listed in Table 1, where T_{in}, T_{dur} are the duration of the first and second stages of melting; I is the current, A; U is the voltage, V; V is the welding speed (motion of the movable frame), mm/s; P is the pressure in the hydraulic system, atm.; and S is the path, mm.

At each stage (the first stage of melting, the second stage of melting, forcing, precipitation, burr removal), the regression models with output parameters P_{ben} and f_{sag} were constructed and the determination coefficients were calculated, where P_{ben} is the bending force, kN; f_{sag} is the sag, mm; S_{fl}, S_{in} is the path traversed by a frame for a flashing allowance and at the initial stage, mm; the subscripts “avg”, “min” and “max” mean average, minimum, and maximum:

— model of the first stage of melting is

$$\begin{gathered} P_{ben} = 5129.96 + 49.02V_{av} + 9.63V_{min} + 12.54V_{max} \\ - 10.14S_{fl} - 3.92S_{in} - 51.61P_{av} + 6.82P_{min} \\ + 19.54P_{max} + 8.59U_{av} - 7.95U_{min} - 2.69U_{max} \\ - 3.72I_{av} + 1.51I_{min} - 1.21I_{max} - 2.24T_{dur}, \\ R^2 = 0.24, \end{gathered}$$

$$\begin{gathered} f_{sag} = -100.44 + 3.22V_{av} + 1.01S_{in} - 2.96P_{min} \\ - 0.61P_{max} + 0.55U_{av} - 0.35U_{max} + 0.08I_{av} \\ + 0.10I_{max} - 0.22, \\ R^2 = 0.50; \end{gathered}$$

— model of the second stage of melting is

$$\begin{gathered} P_{ben} = 11497.07 + 57.11V_{av} + 178.46V_{min} - 86.14V_{max} \\ - 6.99S_{fl} - 2.12S_{in} - 119.85P_{av} - 69.42P_{min} \\ - 21.97P_{max} - 11.16U_{av} + 0.45U_{min} - 0.49U_{max} \\ + 2.40I_{av} + 5.24I_{min} + 1.70I_{max} - 0.22T_{dur} - 1.39T_{in}, \\ R^2 = 0.20, \end{gathered}$$

$$\begin{gathered} f_{sag} = -436.24 + 1.92V_{av} + 7.94V_{min} - 0.49V_{max} \\ + 5.92S_{fl} + 0.332S_{in} - 0.03P_{av} - 0.24P_{min} \\ - 4.47P_{max} + 0.56U_{av} + 0.07U_{min} - 0.11U_{max} + 0.22I_{av} \\ - 0.05I_{min} - 0.02I_{max} - 0.03T_{dur}. \\ R^2 = 0.27; \end{gathered}$$

— model at the forcing stage is

$$\begin{gathered} P_{ben} = 5792.22 + 159.64V_{av} + 60.29V_{min} + 33.69V_{max} \\ + 4.72S_{fl} - 15.53S_{in} + 52.83P_{av} - 130.84P_{min} \\ + 55.38P_{max} - 11.82U_{av} + 0.15U_{min} + 11.43U_{max} \\ - 4.71I_{av} - 0.35I_{min} - 0.29I_{max} + 14.28T_{dur} - 0.29T_{in}, \\ R^2 = 0.15, \end{gathered}$$

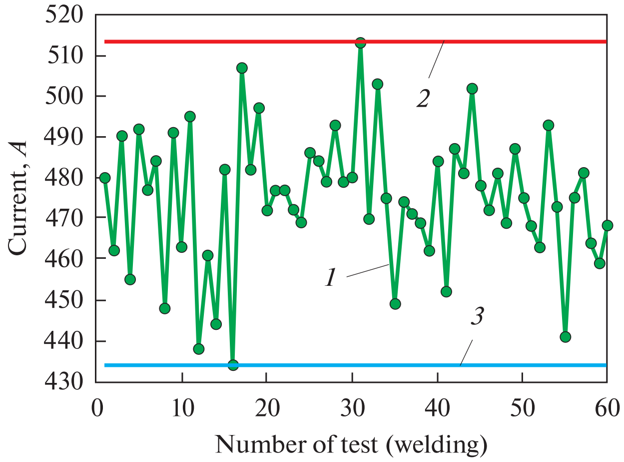

Fig. 2. Spread of the average currents at the I-st melting stage: (*1*) actual value; (*2* and *3*) maximum and minimum.

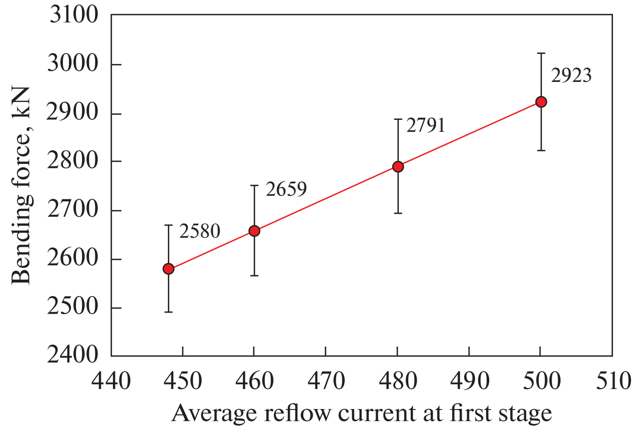

Fig. 3. Dependence of bending force on the average current at the I-st melting stage.

$$f_{sag} = -75.95 - 4.68V_{av} + 4.30V_{min} + 1.47V_{max} + 1.90S_{fl} - 0.37S_{in} + 0.82P_{av} - 2.30P_{min} - 2.98P_{max} + 0.19U_{av} - 0.04U_{min} + 0.21U_{max} + 0.04I_{av} - 0.02I_{min} + 0.57T_{dur}.$$

$$R^2 = 0.20;$$

— model at the precipitation stage is

$$P_{ben} = -1856.13 + 200.10V_{av} - 43.91V_{min} + 6.52V_{max} - 18.40S_{fl} - 15.05S_{in} + 22.56P_{av} - 3.32P_{min} + 61.72P_{max} + 7.28U_{av} - 0.07U_{min} - 13.67U_{max} - 2.63I_{av} - 0.19I_{min} + 3.92I_{max} + 39.64T_{dur} - 0.43T_{in},$$

$$R^2 = 0.24,$$

$$f_{sag} = -161.50 + 2.00V_{av} - 0.01V_{min} + 0.16V_{max} - 0.14S_{fl} - 0.26S_{in} - 0.82P_{av} + 0.10P_{min} + 2.42P_{max} + 0.11U_{av} - 0.06U_{max} - 0.02I_{av} - 0.01I_{min} + 0.03I_{max} + 0.79T_{dur} - 0.01T_{in},$$

$$R^2 = 0.15;$$

— model at the burr removal stage is

$$P_{ben} = 2878.60 + 941.99V_{av} + 72.97V_{max} - 128.93S_{fl} - 1.88S_{in} + 104.21P_{av} - 84.19P_{min} - 13.36P_{max} + 5.19U_{av} - 102.99U_{min} + 54.51U_{max} + 19.41I_{av} - 0.55I_{min} - 20.33I_{max} - 0.47T_{in},$$

$$R^2 = 0.36,$$

$$f_{sag} = 97.35 - 36.29V_{av} - 2.95V_{max} + 2.83S_{fl} - 0.13S_{in} + 3.31P_{av} - 2.08P_{min} - 1.30P_{max} + 1.09U_{av} - 3.80U_{min} + 0.91U_{max} + 1.56I_{av} - 1.07I_{min} - 0.56I_{max},$$

$$R^2 = 0.18.$$

The determination coefficients for each model are low. This suggests that the input variables at each individual stage of the contact welding do not fully reflect their impact on the output parameters. It is obvious that each stage effects on the output parameters but the full impact of the input variables can only be determined in total of these stages.

Having excluded the unsatisfactory parameters according to Student's *t*-criterion and collected the significant parameters of each stage in one equation, we obtain the following models that describe the whole process for the K1100 machine

$$P_{ben} = 814.08 - 12.93I_{max\,5} + 40.84U_{max\,5} - 0.64T_{in4} - 0.26I_{min\,4} + 3.20I_{max\,4} - 6.29_{max\,4} - 2.12P_{min\,4} + 41.79P_{max\,4} + 53.33V_{av4} + 6.60I_{av1} - 219.91P_{av1},$$

$$R^2 = 0.79;$$

$$f_{sag} = -194.21 - 0.24I_{max\,5} - 0.02T_{in4} + 0.07I_{max\,4} + 2.43P_{max\,4} - 0.75P_{av4} + 1.94V_{av4} + 0.01I_{max\,3} + 0.05T_{dur4} + 0.08I_{av1} - 3.32P_{av1},$$

$$R^2 = 0.71.$$

After removing the outliers, 62 observations out of 79 remained. The significance according to Fisher's F-test is (for P_{ben} at significance level $\alpha = 0.05$: $F_{act} = 9.88 > F_{cr} = 0.38$; for f_{sag} at significance level $\alpha = 0.05$: $F_{act} = 6.90 > F_{cr} = 0.38$). For P_{ben}, the mean approximation error is 2.8%. For f_{sag}, the mean approximation error is 5% (under the condition $\varepsilon \leq 10$).

The current range of the first stage is shown in Fig. 2. The welding modes with changed significant parameters are shown in Table 2. The operation of the model with a change in the parameter I_{av} at the first stage is shown in Fig. 3.

Table 2. Welding modes with a modified value of I_{av1} and production parameters

Parameter	P_{av1}, atm	I_{av1}, A	V_{av4}, mm/s	P_{max4}, atm	P_{min4}, atm	U_{max4}, V	I_{max4}, A	I_{min4}, A	T_{in4}, s	U_{max5}, V	I_{max5}, A	P_{den}, kN	f_{sag}, mm
Mode	31	448	8.56	123	99	372	1109	975	128.3	102	314	2670	37.1
Model	31	448	8.56	123	99	372	1109	975	128.3	102	314	2580	38.2

Table 3. Optimal parameters of K1100 machine

Parameter	P_{av1}, atm	I_{av1}, A	V_{av4}, mm/s	P_{max4}, atm	P_{min4}, atm	U_{max4}, V	I_{max4}, A	I_{min4}, A	T_{in4}, s	U_{max5}, V	I_{max5}, A
Sign of equation	–	+	+	+	–	–	+	–	–	+	–
Minimum	30	434	1.56	123	25	359	1074	6	99.1	2	6
Maximum	32	521	9.33	129	124	423	1174	1075	144.9	105	324
Optimal	30	521	9.33	129	25	359	1174	6	99.1	105	324

The correlation between the bending force and deflection of the bending test, depending on the machine used, is shown in Fig. 4. Thus, it is clear that the process can be modeled by one dependent variable only since the second variable also changes.

At this stage, according to the obtained models, the optimal parameters were found based on the signs of the regression coefficients (Table 3). When the most favorable parameters are selected, the bending force P_{ben} is 8437.37 kN. The calculated value of P_{ben} is almost three times higher than the average one. These modes cannot be implemented in the real process since there is no reflow at the fifth stage, the current already flows through the total cross section of a welded rail. As a result, it is not possible to adjust the reflow current by moving the movable frame (in this case, current is proportional to voltage). Therefore, the simultaneous substitution of minimum voltage and the maximum current is incorrect. By substituting first the maximum values and then the minimum values of voltage and current of the fifth stage (U_{max5}, I_{max5}), we obtain the bending forces closest to the true values 3923.07 and 3828.29 kN, respectively. Thus, the presence of current after precipitation in the welded rails has a positive effect on the quality of a welded joint. The value of T_{in4} also indicates that the minimum melting time allows one to obtain the best quality indicators. The bending force and sag, which are predicted by these regression models, are 3923.07 kN and 75.83 mm, respectively.

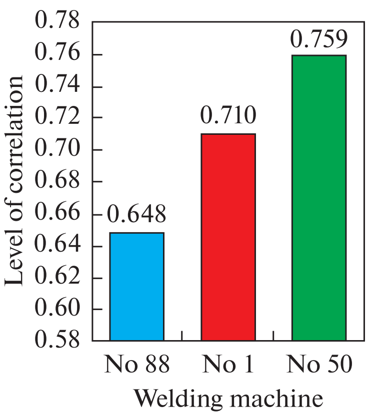

Fig. 4. Correlation between the bending force and deflection boom during bending tests depending on the used machine.

CONCLUSIONS

The mathematical models of the contact butt welding of rails using a K1000 machine have been developed, which make it possible to estimate the completeness of the effect of technological parameters of the contact butt welding of rails on the quality of a weld. Based on the regression models, it is suggested to predict the quality of a weld and control the technological parameters of the contact butt welding of rails. Based on the selection of significant factors, the general models of the welding process are obtained considering the effect of parameters of each stage on the whole welding process. The approbation of the obtained models at a rail welding enterprise is carried out. It is revealed that one of the reasons for a decrease in the mechanical properties of rails, namely the bending force and sag, is the inability to maintain the average current during the modes at each stage.

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