https://doi.org/10.37434/tpwj2021.05.01

OPERATIONAL CONTROL OF THE PROCESS OF FLASH BUTT WELDING OF RAILWAY RAILS BY THE METHOD OF PULSATING FLASHING

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The article presents a study of the accuracy of reproduction of parameters of operational control of flash butt welding of railway rails in order to increase the reliability of evaluating the compliance of the process to the Technical Specifications (TS) and improve the quality of welded joints. For the statistical analysis of protocols of welding rails at rail-welding enterprises the review of existing indices of accuracy and stability of technological processes was made. For the analysis, the coefficient of variation K_v was chosen, which is not related to the tolerance of the deviation of the process parameter. Evaluations of K_v coefficients according to the welding protocols of more than 10 thou joints and more than 100 specimens of a technological test for the stationary machine K1000 showed that the mode parameters set directly by the control system, are reproduced with an error of not more than 1.5 %. The K_v coefficients increase sharply for the rate of flashing, transition from flashing to upsetting and particularly upsetting, which are included in the TS for welding rails and an active electric power, that occurred during flashing at the input of the welding transformer. The studies of K_v coefficients with grouping of welding data by six months showed that the variation of process parameters had no trends and the process was stable over time with a sufficient accuracy. The mean values and the standard deviation of the parameters of the process of welding rails and specimens of a technological test differ within the statistical error, which indicates the possibility of approximating the results of test studies on the rail joints. Evaluation of effect of parameters of the process of rate, tolerance and energy of flashing on the heat-affected zone (HAZ) with the use of linear regression dependence showed an essential dependence of HAZ on variation of electric energy during flashing. For control of active energy, the measuring converter of average active electric power with a pulse output was developed, which is adapted to the control systems of K1000 and K922 machines with input signals of current to 1000 A and voltage to 440 V, a frequency band of these signals to 1 kHz and the resulted error of measurement to 1 %. It is recommended to include active electric power released during flashing at the input of the welding transformer in the list of control parameters to the TS, and to improve the quality of joints not only to control the parameters within tolerance, but to create the conditions of the smallest variation of parameters from obtained data. 7 Ref., 1 Table, 4 Figures.

Keywords: flash butt welding, railway rails, statistical control, coefficient of variation, process parameters, quality parameters, heat-affected-zone, active electric power during flashing, quality control

Technical specifications of flash butt welding (FBW) of railway rails [1, 2] regulate the parameters of welding mode, deviation tolerances for them, quality of a welded joint: width of heat-affected-zone (HAZ), hardness of the metal on the rolling surface of the welded joint and indices of periodic process control according to the specimens of a technological test on static mechanical bending: minimum L_{fr} and fracture load P_{fr}.

The indices of a joint quality, as well as the results of mechanical tests of specimens depend on the deviations of more than a dozen process parameters from their values, for which the process was adjusted.

Scattering of values of both input parameters and, respectively, output quality indices due to the presence of systematic and random perturbations is usually characterized by a mathematical expectation or the mean value of $\bar{x}$ and the variance σ^2 or the root mean square (r.m.s.) or a standard deviation $S = \sqrt{\sigma^2}$ from the average one. If we take into account that the input parameters have different physical properties or differ significantly in values, it is better to use dimensionless values to compare them.

At the statistical control of process indices of accuracy and stability: coefficients of accuracy K_{acc}, adjustment K_{adj} and stability K_{st} are as a rule used:

$$K_{acc} = 6S/\delta,\ K_{adj} = (\bar{x} - x_\delta)/\delta,\ K_{st} = S_{t1}/S_{t2}, \qquad (1)$$

where $\delta = x_u - x_l$ is the tolerance field for the parameter; x_u and x_l is the upper and lower limit of tolerance for the parameter; $x_\delta = (x_u + x_l)/2$ is the middle of the tolerance field; S_{t1} is the r.m.s. at a fixed moment in time t_1; S_{t2} is the r.m.s. at the compared fixed moment of time t_2.

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These evaluations are dimensionless, relative and for their further analysis the physical value of the parameter can be ignored, and for their control the general tolerances can be set, which is convenient for comparing different physical parameters. It is considered, for example, that at $K_{acc} \le 0.75$ the technological process is quite accurate, at $K_{acc} = 0.76–0.98$ the technological process demands careful supervision and at $K_{acc} > 0.98$ the accuracy is unsatisfactory [3].

Many Japanese enterprises and the US automotive industry use similar evaluations for control — process capability indices:

- process potential for bilateral tolerance limits

$$C_p = (x_u - x_l)/6S = \delta/6S,$$

- process efficiency relative to the upper limit of tolerance

$$CPU = (x_u - \bar{x})/3S,$$

- process efficiency relative to the lower limit of tolerance

$$CPL = (\bar{x} - x_l)/3S,$$

- deviation of the average value of the process from the middle of the tolerance field

$$k = 2|x_\delta - \bar{x}|/(x_u - x_l) = 2|x_\delta - \bar{x}|/\delta,$$

- process efficiency for two-sided tolerance limits

$$C_{pk} = \min\{CPU, CPL\} = C_p(1 - k),$$

which form a group of complementary process capacibilty indices and the indices similar to the coefficients K_{acc}, K_{adj} and K_{st}, also determine compliance with the process tolerances and adjustment problems. They can be used for one-sided and two-sided tolerances and can be generalized for operation with multidimensional rated values (quality indices) [4].

The mentioned indices refer to the tolerance field δ, which determines the probability of a quality product when finding a controlled parameter in it. The control of the FBW process of railway rails in stationary machines K1000 and mobile machines K922 in existing machine control systems includes much more parameters than those included in the TS (Table), and not all of them have tolerances. In addition, the tolerances may not be quite «optimal».

Therefore, to compare the spread of parameters in the future the variation coefficient K_v (German Variationskoeffizient m) was used, which is a relative value to characterize scattering (variability) of a feature and it is used at the moment when it is necessary to compare variability of features of an object, expressed in different measurement units (synonym: unitized risk) [3].

The article presents a study of the accuracy of reproduction of the parameters of operational control of FBW of railway rails in order to increase the reliability of conformity evaluation of the process of TS and improve the quality of welded joints.

Tolerances for parameters of flash butt welding of rails of grades M76 of type R65, K76F of type R65, 60E1 by pulsating flashing for the machine K1000 and K922 (in brackets) according to [1]

Parameter	Tolerance field		Study interval	
	Lower	Upper	Lower	Upper
Welding time $^*T_w$, s	60	100	40	275
Flashing rate V_{fl}, mm/s	0.07 (0.065)	0.2	0.03	0.4
Tolerance for flashing S_{fl}, mm	12(9)	18	5	30
Voltage during transition to upsetting U_u, V	355	440	300	500
Flashing voltage U_l, V	250	360	200	500
Rate before upsetting V_f, mm/s	0.7	2.5	0.1	4
Upsetting rate V_{ups}, mm/s	30(20)	80	10	145
Upsetting pressure P_{ups}, atm	12(9)	15(12)-20	5	40
Tolerance for upsetting S_{ups}, mm	11.5	17	5	35
Time of upsetting with current T_{upsI}, s	1-0.49 (0.8)	2(1.8)	0.3	3
Flashing current $^*I_{fl}$, A	–	–	80	800
Impedance of the secondary circuit at a sh.-c $^*Z_{sh.-c}$, μOhm	–	–	25	300
Flashing power $^*Q_{fl}$, kW·h	–	–	1.0	5.00

*Marked parameters that are not included in the TS.

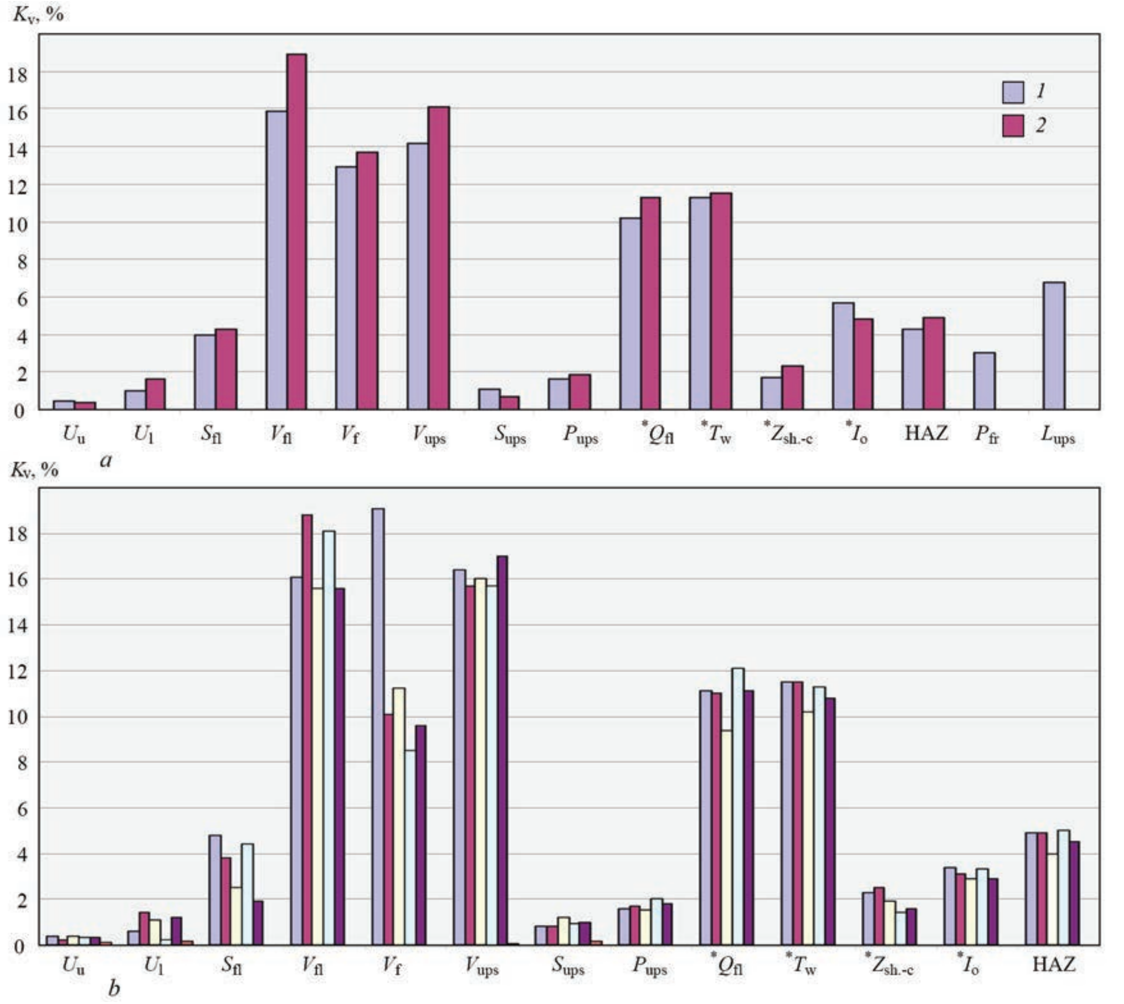

Figure 1. Variation coefficients K_v during welding of R65 rails of grade K76F in the machine K1000 (*a*): *1* — welding data of specimens of a technological test; *2* — welding data of rail joints (hereinafter HAZ was predicted by regression dependence on V_{fl}, S_{fl}, Q_{fl} and S_{ups} [6] and the change of variation coefficients K_v over time with a period of six months during welding R65 rails of grade K76F in the machine K1000. K_v for the same time intervals are shown in the same colour (*b*)

K_v is the ratio of the mean square deviation to the arithmetic mean and is expressed as a percentage: $K_v = S/\bar{x} \cdot 100$ %. Variability is considered to be variable weak if $K_v < 10$ %; average, if K_v is from 11–25 % and significant at $K_v > 25$ %.

Evaluation of the accuracy of reproduction of process parameters, or variation of parameters was performed according to the protocols of welding of railway rails during 2015–2020 at rail welding enterprises (RWE) of Ukrzaliznytsia. For example, according to K_v data of the stationary machine K1000 of the Kyiv RWE, which were calculated by the welding protocols of more than 10 thou joints, the following conclusions may be made (Figure 1).

Among the parameters that determine the compliance of the TS mode, voltage during flashing U_l and during transition from flashing to upsetting, U_u tolerance for flashing S_{fl} and upsetting S_{ups}, upsetting time under current T_{upsI} are set directly in the control system, have a fairly small value of the variation coefficient K_v. P_{ups} is determined by adjusting the pressure in the upsetting cylinder and also has a small K_v. The accuracy of reproduction of these parameters depends entirely on the technical condition of the welding machine, control system and a proper maintenance of external welding conditions, namely, power electricity, pumping station, coolant, etc.

The tolerance for flashing S_{fl} according to the main algorithm of control of FBW of rails is set in the cyclogram of the mode and its correct operation of the system for control of the machine should be close to the accuracy of the sensor for control of the movement of the moving column of the welding machine. Typically, this sensor is based on an incremental sensor Siemens 6FX2001, it has a measurement discreteness of 0.1 mm and the effect of electromagnetic interference on the measurement accuracy is impossible. In the mentioned data, the variation S_{fl} is much higher due to the fact that during welding of a new batch of rails, it is possible to adjust the mode, which was usually performed by changing the specified tolerance for flashing. According to K_v data for eight K1000 machines

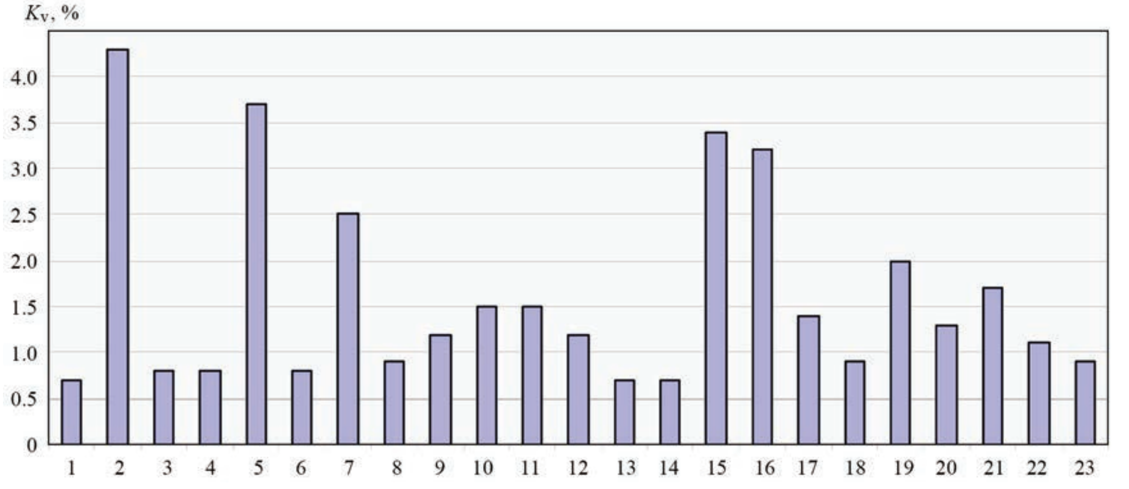

Figure 2. Coefficients K_v for tolerance for flashing S_{fl} of eight machines K1000 (1–8) and 15 machines K922 (9–23)

and fifteen K922 machines of different RWE it is seen that only in the case of mode resetting, the variation of parameter S_{fl} is quite large. At the constant set mode, K_v is lower than 1.0–1.5 % (Figure 2). It is clear that according to other algorithms, for example, the task of time stages, this parameter can have a random distribution with its mean deviation and r.m.s.

The parameters of flashing rate V_{fl}, transition from flashing to upsetting V_f and upsetting V_{ups}, which are included in the TS, shape of current before upsetting (time of probable short circuit $T_{sh.-c)}$, as well as welding time T_w and electric flashing power Q_{fl} are set indirectly and result from the FBW process and, accordingly, from the action of different uncontrolled disturbances.

The rates of flashing V_{fl} and transition to upsetting V_f

$$V_{fl}, V_f = F(V_u, V_l, I_u, I_o, I_l, I_w), \quad (2)$$

where V_u, V_l, I_u, I_u, I_o are the parameters of the regulator of the feed drive of a mobile column depending on welding current I_w;

Welding time

$$T_w = S_c/V_c + S_{fl}/V_{fl} + S_f/V_f + T_{ups}i,$$

where S_c, V_c, S_{fl}, V_{fl}, S_f, V_f is the tolerance and average speed at the stages of bevel removal, flashing and transition to upsetting.

The upsetting rate V_{ups} depends on the set upsetting pressure, technical condition of the upsetting drive and the moving column, and the heating of the welding rails before upsetting. Impedance of sh.c of a secondary circuit $Z_{sh.-c}$ characterizes the technical condition of the machine.

From the listed parameters controlled by the control system of machines K1000 and K922, in terms of K_v the most vulnerable indices are the rates V_{fl}, V_f, V_{ups} and welding time T_w and electrical power released at

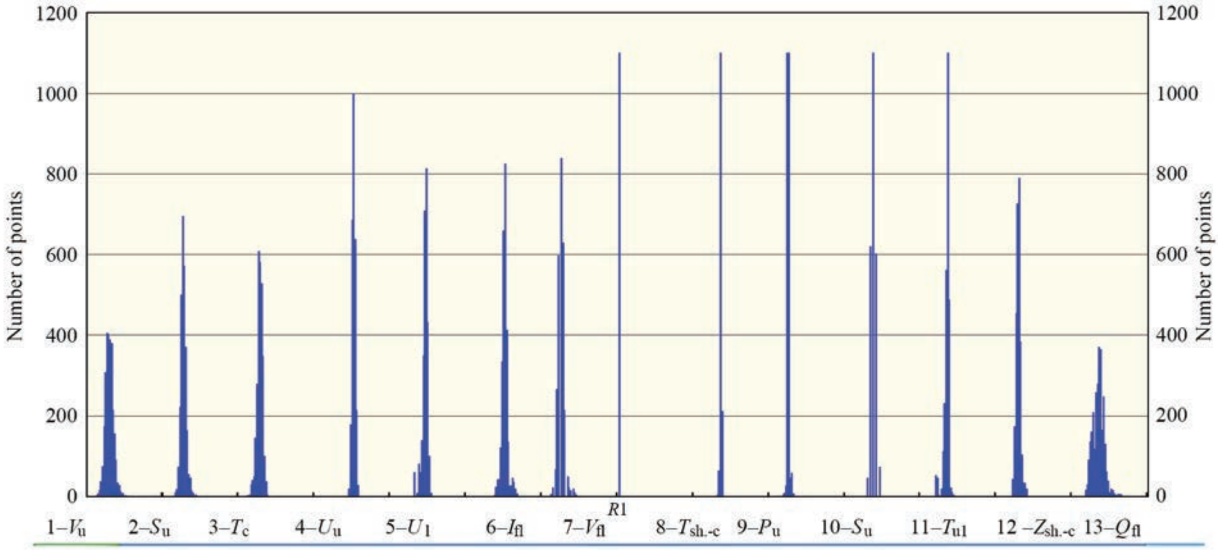

Figure 3. Histogram of distribution of process parameters of FBW of 10230 rail joints in the machine K1000, which was calculated on the interval of studies for each parameter (Table), number of intervals for all parameters was 50, step of each parameter is $\Delta X = (X_{u.f} - X_{l.f})$, where $X_{u.f}$ and $X_{l.f}$ are upper and lower intervals of studies (for example, for ΔS_{fl} = (30-5)/50 = 0.5 mm)

Figure 4. Coefficients of accuracy K_{acc} (*a*) and adjustment K_{adj} (*b*) during welding of R65 rails of grade K76F in the machine K1000 (*1* — data on welding of specimens of technological test; *2* — data on welding rails)

the input of the welding transformer at the flashing stage, Q_{fl} (Figure 1). It should be noted that in addition to the action of perturbations, the r.m.s. of rates V_{fl} and V_f is influenced by the fact that the error of their measurement approaches the absolute value of the measured value.

The measurement of rates is performed according to the displacement sensor and the absolute error is $\Delta V = 0.1$ mm / T_{meas}, where T_{meas} is the interval between measurements. The measurement discreteness of the control system in time is equal to 0.01 s. Therefore, we have either a very large static error or a large dynamic error for stabilization of these parameters.

According to the data of histograms (Figure 3) reproduction of FBW process parameters, in particular V_{fl}, V_f, V_{ups}, it is possible to make an assumption that the distribution of error of these parameters concerning average value corresponds to the normal law.

The calculation of the accuracy coefficients K_{acc} (1), which take into account the value of the tolerance field and are accepted for statistical control of technological processes, confirms the general ratio of the accuracy of reproduction of the parameters C_v (Figure 4). According to the accuracy coefficient K_{acc}, which takes into account the tolerance for deviation of parameters according to TS (see Table), it is seen that provided that the average value of the rate V_{fl}, V_f, V_{ups} is close to the middle of the tolerance field, we have a probability of TS conformity more than 99.7 % of joints. For other parameters, the condition of finding the average value in the middle of the tolerance is already not so rigid.

To identify any trends over time, for example, changes in the technical condition of the welding machine, the coefficients K_v and K_{acc} were calculated with an interval of six months (Figures 1, *b*, 4, *b*). It is seen that during the control period the welding process was unchanged in terms of variation of FBW parameters and control data of technological test specimens (see Figure 1) for these parameters correspond to the process of welding rails (average values and r.m.s. parameters differ within the statistical errors, see K_{adj} and K_{acc} in Figure 4) and testing data of specimens by technological test can be used to evaluate the quality of rail joints.

The influence of output deviation from deviation of input parameters, among other factors, depends on possible interrelationships between inputs. The total variance for multifactor process in the case when the factors are not related to each other consists of the sum of the variances of each factor. In the case of correlated factors, the components of covariance are added to this sum with the corresponding sign — the measure of joint variability of two random variables. The absolute deviation of the output of the function $Y = f(x_1, x_2 \ldots x_n)$ from the deviation of any parameter $\Delta x_i = S_i$ at the point $x_i = \bar{x}_i$, $i = 1 \ldots n$, through K_{inp} depends on the value of the parameter $x_i = \bar{x}_i$ and a partial derivative $\partial Y/\partial x_i$ of the parameter $x_i = \bar{x}_i$ at this point $\Delta Y = \partial Y/\partial x_i \bar{x}_i K_{inp}$. In the same way we can show that the accuracy coefficient is equal to

$$K_{acc} = 6 \bar{x}_i K_{inp}/\delta. \quad (3)$$

The influence of each input factor is a partial derivative $\partial Y/\partial x_i$ can be evaluated by the mathematical dependence of an output parameter on input parameters. For example, flashing rate V_{fl}, tolerance for flashing S_{fl}, electric power during flashing Q_{fl} determine the temperature field in FBW. Mathematical regression dependences of HAZ on V_{fl}, S_{fl}, and Q_{fl} were obtained using experimental data and a mathematical model of a temperature field kinetics during continuous flashing, taking into account the multifactorial effect of transient processes of formation and destruction of single contacts on heating intensity, which formed during the technological cycle of flash butt welding of railway rails [5, 6]. To evaluate the effect of parameter deviations on HAZ in the case of using the simplest first-order dependence, we have

$$L_{HAZ} = a_0 + a_1 V_{fl} + a_2 S_{fl} + a_3 Q_{fl} - S_{ups}.$$

The deviation of the HAZ width from the value at the average process parameters has the form:

$$\Delta L = L - L(V_{fl} = \bar{V}_{fl}, S_{fl} = \bar{S}_{fl}, Q_{fl} = \bar{Q}_{fl}) =$$
$$= a_1(V_{fl} - \bar{v}_{fl}) + a_2 (S_{fl} - \bar{S}_{fl}) + a_3 (Q_{fl} - \bar{Q}_{fl}) - (S_{ups} - \bar{S}_{ups}) =$$
$$= a_1 \bar{S}_{fl\,l} K_{vS_{fl}} + a_2 \bar{V}_{fl} K_{vV_{fl}} + a_3 \bar{Q}_{fl} K_{vQ_{fl}} + \bar{S}_{ups} K_{vS_u} =$$
$$= -23K_{vSfl} + 4K_{vVfl} + 34 K_{vQ} - \Delta S_{ups}.$$

Thus, despite the fact that $K_{vS_{fl}}$ is much lower than $K_{vV_{fl}}$, the effect of the deviation of tolerance on quality of the welded joint is almost the same as flashing rate. At the same time, we have a significant influence on flashing electric power $K_{vQ_{fl}} \approx 3K_{vS_{fl}}$, and it becomes important to control the electric power during flashing Q_{fl} and its introduction into the list of parameters of the TS for welding rails (Table).

The complexity of measuring active power is associated with the fact that the harmonic component of active power is determined by those harmonics that are represented in the current signal and in the voltage signal. According to the computer simulation data, the signals of current, voltage and power on frequency spectrum are placed at the input of the power transformer in the range of angles φ (from 0 to 90°) and angles of switching the thyristor contactor α (from φ to 120°) in the range of up to 1 kHz. These results were confirmed experimentally by recording the welding current and voltage at the input of a power transformer with a frequency of 10 kHz and a subsequent calculation of active power. To control the power Q_{fl} at the PWI a measuring transducer of average active electric power with a pulse output was designed on the basis of the industrial controller Siemens CPU 314C-2PTP or CPU1512C-1PN with input signals of up to 1000 A current and a voltage of up to 440 V, a frequency band of these signals of up to 1 kHz and a resulting measurement error of up to 1 %, which is adapted to the control systems of machines K1000 and K922.

According to the data of welding specimens of a technological test at RWE, which passed testing on static bending and were recognized as those which meet TS, it is seen that K_v of a deflection L_{fr} and a destructive force P_{fr} is almost 2 times lower than K_v of parameters of flashing rate, forcing and upsetting (Figure 1, *a*). The parameters set directly by the control system of the machine, on the contrary, have K_v almost 2 times lower than that for the indices of a joint quality. Thus, we can very cautiously assume the most significant contribution of these rates to quality. But these parameters are definitely the most vulnerable in terms of the abilities of accuracy of operation of the control system in the reproduction of the desired values of V_{fl}, V_f, V_{ups}. In addition, taking into account the influence of the parameters on the HAZ width it is necessary that the list of control parameters in the TS (Table) was added by the value of electric power released during flashing.

When choosing the tolerance field, it should be taken into account that while solving any statistical hypothesis, two types of errors are possible:

- the error of the first kind consists in the fact that the hypothesis which is actually true is rejected — in our case the qualitative joint will be recognized as a low-quality one;

● the second kind of error consists in the fact that the hypothesis is accepted, but it is actually incorrect — a poor joint will be recognized as a high quality one.

The boundary between the signs of conformity and nonconformity of the TS is quite blurred and if the probability of errors can be evaluated, it should be chosen taking into account the cost for replacement of a quality joint in the lash (in the first case) and the cost of tolerance of a poor joint in the lash in the other. It is quite natural in this case to choose more rigid tolerances for the control of parameters. According to data on HAZ predicting, it is clear that the most objective evaluations of tolerances can be obtained from the analytical dependences of quality indices on process parameters, which in the case of FBW is currently impossible.

It should be noted that although the control of tolerances is a very common means of preventing rejection, the example of setting the tolerance for flashing for different batches of rails shows that the tolerance S_{fl} in the TS can meet a wide range of quality values, and the variation S_{fl} itself for the set mode is much lower than the tolerance. Thus, the condition of tolerance does not use all the features of welding equipment and technology in general.

According to the method of production management [7], it is considered that compliance with the tolerances of control factors is an insufficient criterion to judge about the quality of products. It is necessary to constantly strive for the rated value, which was obtained when setting the mode, and to reduce the variation of factors, even within the limits set by the project. In this case, the adjustment of the optimal levels of control factors of the process is performed by achieving the optimal ratio «signal/noise», which in our case corresponds to the inverse value of the variation coefficient K_v.

Conclusions

1. Statistical studies on the protocols of the FBW process of railway rails at RWE showed that the parameters of control of the butt welding process, which are given in the TS and set directly by the control system of the welding machine, do not significantly depend on external perturbations and are reproduced with an accuracy of a control system stabilization.

2. The parameters, the values of which are the result of the welding process and the action of uncontrolled perturbations, namely flashing rates, transition to upsetting, upsetting and active electric power released at the joint, are reproduced with an error of 5–10 times higher than the control system error.

3. To increase the accuracy of control of the FBW process of rails, the list of control parameters in the TS for welding rails, it is appropriate to introduce the control of active electric power at the input of the welding transformer during flashing. At the PWI, a sensor for monitoring such power was designed, which is adapted to the existing control system of welding machines.

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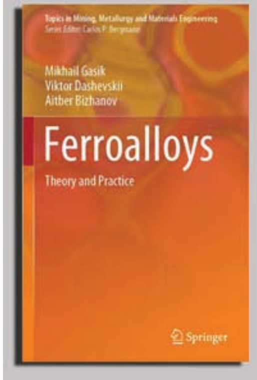
Received 05.04.2021

NEW BOOK



Springer Publishing house (Switzerland) has released in 2020 a new book **«Ferroalloys: theory and practice»** (530 p.) by Gasik M.I., Dashevskii V.Ya., Bizhanov A.M., under supervision of Academician of National Academy of Sciences of Ukraine, Professor Mikhail Ivanovich Gasik.

This book outlines the physical and chemical foundations of high-temperature processes for producing ferroalloys with carbo- , silico- and aluminothermal methods, as well as technology practice for manufacturing of ferroalloys with silicon, manganese, chromium, molybdenum, vanadium, titanium, alkaline earth and rare earth metals, niobium, zirconium, aluminum, boron, nickel, cobalt, phosphorus, selenium and tellurium and also iron-carbon alloys. The chapters introduce the industrial production technologies of these groups of ferroalloys, the characteristics of charge materials, and the technological parameters of the melting processes. Special chapters are devoted to description of ferroalloy furnaces and self-baking electrodes in detail. Additionally, topics related to waste treatment, recycling, and solution of environmental issues are considered.

The book is recommended for specialists and researchers involved in the international ferroalloys production.

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