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Controlling the Welding Process in Robotic Technological Complexes by the Criterion of Product Quality

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The solution of the problem of controlling the arc welding process by robotic technological complexes by the quality criterion of the produced products is proposed in this paper. The statement of the problem is given, the criterion of the quality in the form of the goal function is described. The mathematical models based on the principles of J. Forrester's system dynamics is developed. The main indicators that affect the quality of the welding process in RTC and their relationships are identified as system levels. The external factors that depend on the indicators and affect them are also defined. The functional dependencies of the indicators were obtained as a result of approximation of statistical data based on long-term observations of the process. A system of the differential equations that describe the cause-effect relationships between the indicators and the factors is developed. Based on the mathematical model, an algorithm for the search for control actions, the implementation of which minimizes the goal function was developed. The developed models and the control algorithms might significantly improve the quality of the arc welding process. The proposed software is testing as a part of the RTC Kawasaki technical control system at OJSC "Transmash" (Engels, Russia).

Keywords: *robotic technological complex, technological process, system dynamics, level of quality, mathematical model*

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Управление процессом сварки в роботизированных технологических комплексах по критерию качества производимой продукции

Предлагается решение задачи управления процессом дуговой сварки роботизированными технологическими комплексами, основанное на принципах системной динамики Дж. Форрестера. Разработаны математические модели и алгоритмы, позволяющие значительно повысить качество дуговой сварки. Предложенное математическое обеспечение проходит апробацию в составе комплекса системы управления роботизированными комплексами Kawasaki на ОАО "Трансмаш" (г. Энгельс).

Ключевые слова: *роботизированный технологический комплекс, технологический процесс, системная динамика, показатель качества, математическая модель*

Introduction

The welding process in robotic technological complexes (RTC) requires constant evaluation of the quality of the products produced at all stages of the technological process. The lack of quality control at any stage, for example, due to the deviation from welding parameters or the lack of quality control inspectors (QCI), increases the risk of defective products.

Currently, various quality control systems for welding in RTC use in practice [1—6]. The main attention is paid to ensuring the observance of welding parameters and the accuracy of positioning of the welding torch. However, in these systems, insufficient attention is paid to optimizing the operational control of the welding process in the RTC by the criterion of the quality of the products. These arguments determine the relevance and practical value of the development and implementation of new mathematical models and algorithms that allow the control of the welding process by robotic technological complexes according to the criterion of the quality of the products.

Mathematical model and algorithm

It is necessary to develop mathematical models and algorithms that allow us to find the control action vector $p(t) \in \{p\}$, on the time interval $[t_S, t_F]$, minimizing the objective function

$$Q(t) = \int_{t_S}^{t_F} \sum_{i=1}^{n} (X_i^*(t) - X_i(t))^2 \omega_i dt \to \min, \quad (1)$$

where X_i, $i = 1,2, ..., n$ are actual parameters of the welding process; X_i^* (t) is the specified value of the indicator X_i, ω_i is the weight coefficient of the i-th indicator.

Minimization of functions $Q(t)$ is associated with significant difficulties due to the high dimensionality and complexity of the control object and the need to take into account a large number of parameters. Therefore, to describe the interrelation between the elements of the welding technological process in the RTC, the model of J. Forrester's system dynamics was chosen, which allows constructing differential equations of the form

$$\frac{dI_j}{dt} = \alpha_{j,0} + \sum_{k=1}^{n} \alpha_{j,k} \prod_{l=1}^{n} \omega_{j,k,l}(I_l) I_k, \; j = 1,\dots,n, \quad (2)$$

where I_1, ..., I_n are system levels characterizing the simulated phenomenon; $\alpha_{j,k}$, is $k = 1$, ..., n; the rate of the j-th stream, i.e. rate of changing I_k; $\omega_{j,k,l}$ — are factors for each level [7—9].

Based on the operational experience of the RTC with the Kawasaki manipulators on the C40 controllers and the welding equipment Fronius for solving the problem (1), 18 parameters were identified as system levels (Table 1).

Table 1

The quality indicators for welding in robotic technological complexes

Sign	Name of parameter
X_1	Number of defective beams per 100 items
X_2	Number of RTC operators
X_3	Average number of RTC stops per cycle
X_4	Average length of defective welds per unit of production
X_5	Completed work on scheduled maintenance of RTC
X_6	Number of programmers
X_7	Number of adjusters of welding equipment
X_8	Number of QCI
X_9	Number of workshop technologists
X_{10}	Days of delay in the supply of materials and spare parts for repair of RTC
X_{11}	Average deviation of welding arc voltage
X_{12}	Average current deviation on the feed unit motor VR1500
X_{13}	Average deviation of the manipulator from the program trajectory
X_{14}	Availability of necessary technological documentation at workplaces
X_{15}	Deviation of the shield gas pressure
X_{16}	Deviation of compressed air pressure
X_{17}	Production plan for a period, in units
X_{18}	Number of beams approved by QCI from the first time

In addition, the model includes external factors that depend on the above characteristics and affect them (Table 2).

Table 2

The factors that influence the quality indicators

Sign	Name of factor
Sm	Number of shifts in production
Rw	Number of RTC involved in the production process
N_{st}	The number of RTC stops for the period
S^*	Permissible number of RTC stops per welding cycle
O_0	Number of RTC operators at the beginning of the period
O_{in}	Number of RTC operators hired for the period
O_{out}	Number of dismissed RTC operators for the period
Ld	Total length of defective weld seams for the period
L^*	Estimated length of defective weld seams for the period
M_f	Number of completed activities of the scheduled preventive maintenance of RTC
M_p	Number of planned activities of the scheduled preventive maintenance of RTC
P_0	Number of programmers at the beginning of the period
P_{in}	Number of hired programmers for the period
P_{out}	Number of dismissed programmers for the period

End of table 2

Sign	Name of factor
R_0	Number of adjusters of welding equipment at the beginning of the period
R_{in}	Number of hired adjusters of welding equipment for the period
R_{out}	Number of dismissed adjusters of welding equipment for the period
C	Number of QCI at the beginning of the period
C_{in}	Number of QCI hired for the period
C_{out}	Number of dismissed QCI for the period
T_0	Number of workshop technologists at the beginning of the period
T_{in}	Number of workshop technologists hired for the period
T_{out}	Number of workshop technologists for the period
Nr	Duration of repair of RTC
D_f	Actual delivery time of spare parts and materials for repair of the RTC
D_p	Planned delivery time of spare parts and materials for repair of RTC
Δ_U	Average deviation of the welding arc voltage from the nominal value
Δ^*_U	Permissible deviation of the welding arc voltage from the nominal value
Δ_I	Average deviation of the current on the motor of the wire feed unit from the nominal value
Δ^*_I	Permissible current deviation on the motor of the wire feed unit from the nominal value
Δ_T	Average deviation of the manipulator from the programmed trajectory
Δ^*_T	Permissible deviation of the manipulator from the programmed trajectory
Td_f	Required number of documents of the technological process
Td_p	Actual number of documents of the technological process
Δ_{PG}	Average deviation of the pressure of shielding gas
Δ^*_{PG}	Permissible deviation of the pressure of shielding gas
Δ_{PV}	Average deviation of the pressure of compressed air
Δ^*_{PV}	Permissible deviation of compressed air pressure
N_{TP}	Number of beams assembled in accordance with the technological process
N_d	Number of beams adopted to QCI from the first presentation for the period
Ab	Number of acts on nonconforming products for the period

Figure 1 shows the graph of cause-effect relationships between the indicators X_1, X_2..., X_{18} affecting the quality of products.

For the variable X_1, the differential equation (2) has the form

$$dX_1(t)/dt = \\ = (N_W f_1(X_3) f_2(X_{11}) f_3(X_{12}) f_4(X_{13})) - \\ - (N_S f_5(X_2) f_6(X_8) f_7(X_{17})). \quad (3)$$

Equations for other variables are compiled in a similar way. As a result the system of equations based on the mathematical model of J. Forrester's system dynamics will look as follows:

$$\begin{cases} dX_1(t)/dt = N_W f_1(X_3) f_2(X_{11}) f_3(X_{12}) f_4(X_{13}) - \\ -N_S f_5(X_2) f_6(X_8) f_7(X_{17}); \\ dX_2(t)/dt = (O_0 + O_{in}) f_{12}(X_{17}) - (Sm + Rw + O_{out}); \\ dX_3(t)/dt = N_{st}/N_W f_8(X_{10}) f_9(X_{15}) f_{10}(X_{16}) - \\ -S^* f_{11}(X_2); \\ dX_4(t)/dt = Ldf_{13}(X_{15}) f_{14}(X_{16}) - L^* f_{15}(X_2); \\ dX_5(t)/dt = M_f f_{16}(X_6) f_{17}(X_7) - M_p f_{18}(X_{10}); \\ dX_6(t)/dt = (P_0 + P_{in}) f_{19}(X_{17}) - (Sm + Rw + P_{out}); \\ dX_7(t) / dt = (R_0 + R_{in}) f_{20}(X_{17}) - (Sm + Rw + R_{out}); \\ dX_8(t)/dt = (C_0 + C_{in}) f_{21}(X_{17}) - (Sm + Rw + C_{out}); \\ dX_9(t)/dt = (T_0 + T_{in}) f_{22}(X_{17}) - T_{out}; \\ dX_{10}(t)/dt = (Nr + D_f) f_{23}(X_{17}) - D_p; \\ dX_{11}(t)/dt = \Delta_U - \Delta^*_U f_{24}(X_5); \\ dX_{12}(t)/dt = \Delta_I - \Delta^*_I f_{25}(X_5); \\ dX_{13}(t)/dt = \Delta_T - \Delta^*_T f_{26}(X_5); \\ dX_{14}(t)/dt = Td_f f_{27}(X_9) - Td_p; \\ dX_{15}(t)/dt = \Delta_{PG} - \Delta^*_{PG} f_{28}(X_{17}); \\ dX_{16}(t)/dt = \Delta_{PV} - \Delta^*_{PV} f_{29}(X_{17}); \\ dX_{17}(t)/dt = N_{TP} f_{30}(X_9) - N_W; \\ dX_{18}(t)/dt = N_d f_{31}(X_6) f_{32}(X_7) f_{33}(X_8) f_{34}(X_{14}) - \\ - (Ab + Ld) f_{35}(X_1) f_{36}(X_4), \end{cases}$$

where $f(X_i)$ is the functional dependence on indicator X_i obtained as a result of polynomial approximation of statistical data.

The analytical solution of the system of equations (3) is difficult due to the high dimensionality and nonlinearity, therefore the values of the parameters X_1, X_2,..., X_{18} are determined by numerical solution.

The solution of the system of equations (3) with the help of logarithmic approximation is presented below:

$$X_1(t) = 0{,}0086\ln(t) + 0{,}0774;$$
$$X_2(t) = 0{,}027\ln(t) + 0{,}6554;$$
$$X_3(t) = 0{,}0525\ln(t) + 0{,}1091;$$
$$X_4(t) = 0{,}0045\ln(t) + 0{,}5534;$$
$$X_5(t) = -0{,}104\ln(t) + 0{,}889;$$
$$X_6(t) = -0{,}051\ln(t) + 0{,}6675;$$
$$X_7(t) = -0{,}116\ln(t) + 0{,}8375;$$
$$X_8(t) = 0{,}0019\ln(t) + 0{,}7596;$$
$$X_9(t) = 0{,}0019\ln(t) + 0{,}7596;$$

$$X_{10}(t) = 0,0258\ln(t) + 0,3417;$$
$$X_{11}(t) = -0,03\ln(t) + 0,3228;$$
$$X_{12}(t) = -0,015\ln(t) + 0,182;$$
$$X_{13}(t) = -0,058\ln(t) + 0,7089;$$
$$X_{14}(t) = 0,016\ln(t) + 0,8241;$$
$$X_{15}(t) = -0,047\ln(t) + 0,5613;$$
$$X_{16}(t) = 0,0359\ln(t) + 0,6723;$$
$$X_{17}(t) = -0,03\ln(t) + 0,9759;$$
$$X_{18}(t) = -0,021\ln(t) + 0,9261.$$

The specified values of the quality indicators of the welding process X_i^*(t) and the weight coefficients ω_i, that necessary for calculating the objective function $Q(t)$, were selected by conducting an expert evaluation based on observations of the technological process.

Further, to solve the problem (1), we need to find the control action vector for minimizing the function $Q(t)$. Control actions are activities plans $\mathbf{p}_j \in \{\mathbf{P}\}$, $j = 1,2,.., N$:

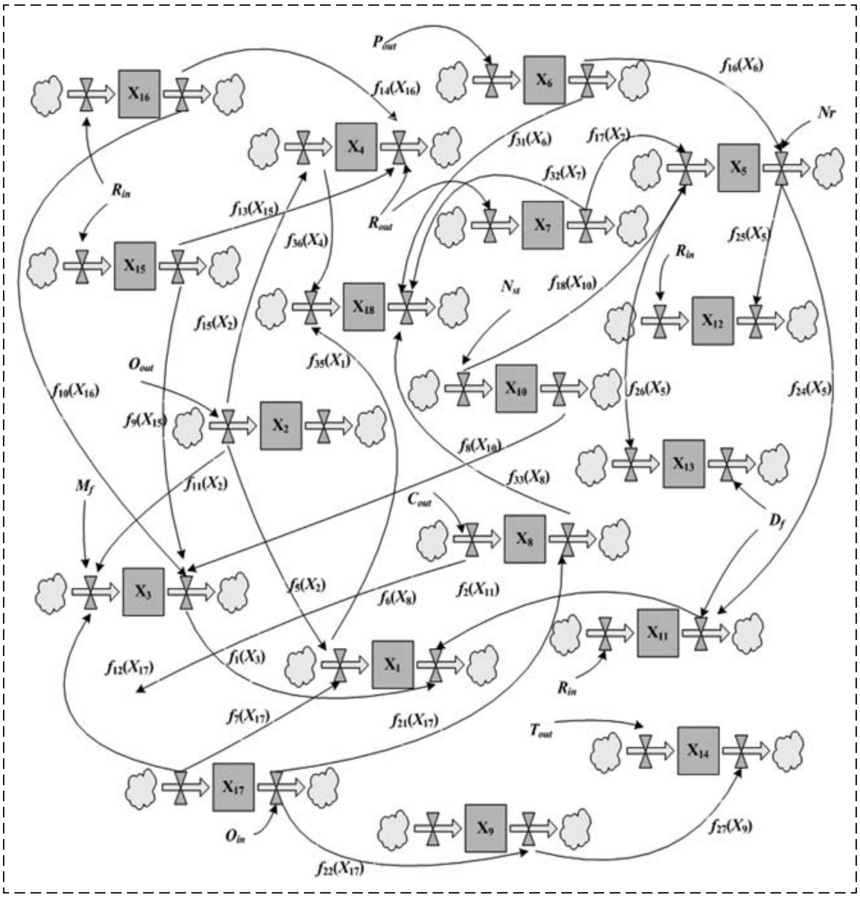

Fig. 1. The graph of cause-effect relationships between the parameters of the arc welding process in RTC

$$p_j : \{X_1(t), X_2(t), \ldots, X_{18}(t)\} \rightarrow$$
$$\rightarrow \{X_1(t) + \delta_1^{(j)}, X_2(t) + \delta_2^{(j)}, \ldots, X_{18}(t) + \delta_{18}^{(j)}\},$$

where — $X_i(t) < \delta_i^{(j)}) < 1 - X_i(t)$, $i = 1,2, ..., 18$, $j = 1,2,...,N$. The values $\delta_1^{(j)}$, $\delta_2^{(j)}$, ..., $\delta_{18}^{(j)}$ was defined by experts taking into account the specifics of the welding process.

Activities plans are based on the frame model:

$$<name; (Act_1; R\_ex_1; Pl_1; T_1); \ldots$$
$$\ldots (Act_M; R\_ex_M; Pl_M; T_M)>,$$

where *name* is the name of activities plan; Act_i is the description of i-th activity; R_ex_i is the responsible executor of i-th activity; Pl_i is the place for i-th activity; T_i is the time of execution for i-th activity.

Calculating the values of the objective function $Q(t)$ for each $\mathbf{p}_j \in \{\mathbf{P}\}$ for a given time interval, it is possible to define an action plan that will allow optimal control of welding quality in the RTC. After that via the searching, the plan is determined, the implementation of which minimizes $Q(t)$.

The results of calculating the function $Q(t)$ for different activities plans are shown in Figure 2.

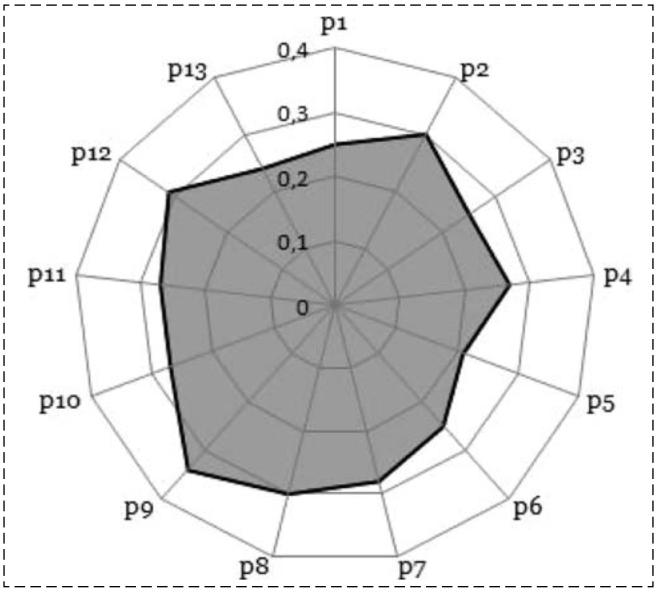

Fig. 2. Calculation of the function $Q(t)$ for the implementation of various activities plans

As follows from the graph in Fig. 2, the minimum of the function $Q(t)$ is achieved when implementing the action plan p_5. This plan in the form of a frame is presented below:

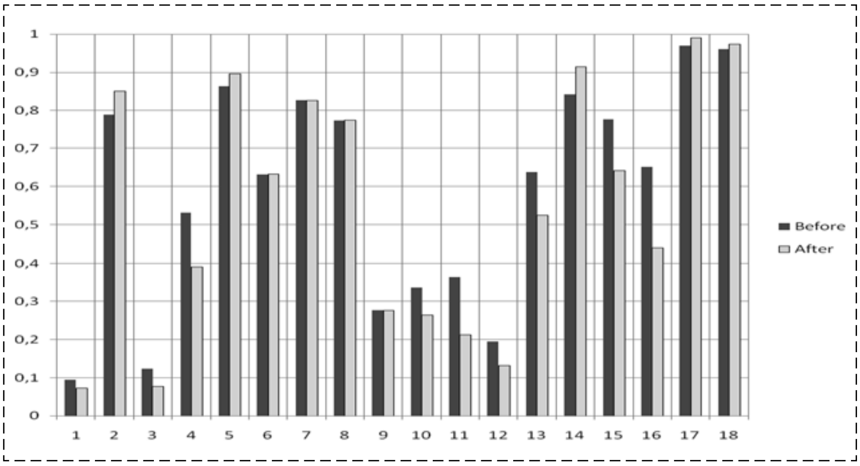

Fig. 3. Values of quality indicators before and after the implementation of the plan p_5

<$\mathbf{p}_5$; (*Perform intermediate quality control of the weld; Operator of RTC; Workshop; Every shift*);

(*Periodically check the relevance of the documentation; Workshop technologist; Workshop; Every day*);

(*Monitor the values of the welding current according to the power supply indicators; Operator of RTC; Workshop; Every hour*);

(*Carry out planned preventive maintenance of RTC; Adjuster of welding equipment; Workshop; Every month*);

(*Hire an additional programmer; HR inspector; HR department; Within a month*)>.

Figure 3 shows a comparison of the values of the quality indicators before and after the implementation of the activities plan $\mathbf{p}_5$.

As we can see from Fig. 3 the implementation of the activities plan $\mathbf{p}_5$ allows to reduce the value of X_1 from 0,095 to 0,08, which means a reduction in the number of defected beams from 11 to 8 per 100 units of production, the value of the indicator X_4 is reduced from 0,532 to 0,398, which is equivalent to a decrease in the average length of defective welded seams with 0,75 m to 0,35 m per 1 unit of production.

Conclusion

The problem of welding process control in robotized technological complexes by the quality criterion of the produced products has been set and solved. Models and algorithms for solving the problem are developed, based on the principles of Forrester's system dynamics.

These models and algorithms allow to significantly improve the quality of welding, and consequently, the quality of products manufactured by enterprises using robotic technological complexes. Currently, the developed software is tested on the basis of a complex of control and measuring equipment RTC Kawasaki at OJSC "Transmash" (Engels, Russia).

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