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MATHEMATICAL MODELING OF THE PROCESS OF METAL HEATING IN CONTINUOUS FLASH-BUTT WELDING

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In the last decade, an urgent and practically significant problem has been producing of high-quality joints of high-strength steels and alloys. For its solution the technologies are required which are distinguished by a high-concentration heating at a minimum energy input, including in continuous flash-butt welding of railway rails. To solve this problem, a mathematical model of the process of metal heating in continuous flash-butt welding was developed. The model allows avoiding labor-consuming and expensive experiments and significantly expanding the range of searching the ways of optimizing at a multifactor control of welding parameters, affecting, in particular, the formation of the temperature field in continuous flash-butt welding of rails. 8. Ref., 12 Figures.

Keywords: *continuous flashing, single contact, mathematical modeling, flash-butt welding, current density, efficiency coefficient, crater depth, spark gap, rail*

Continuous flash-butt welding (CF) is widely used in the leading branches of industry for joining of parts from steels and alloys with different cross-section area. In accordance with acting reference documents [1] this type of welding is recommended for the parts with limited thickness of section elements, which does not exceed 12–15 mm. These recommendations are based on the experience of commercial application of flash-butt welding using existing technologies, which do not often allow providing heating of the larger thickness parts, necessary for quality joints. Besides, in order to excite continuous flashing of such parts without resistance heating it is necessary additionally to increase source supply power. Therefore, in flash-butt welding of the larger thickness parts it is recommend to use flash-butt welding with resistance preheating.

In scopes of investigations, which were carried out at the E.O. Paton Electric Welding Institute of the NAS of Ukraine in the previous years, there were determined the main parameters of CF process, effecting the heating and formation of temperature field in a welding zone [2]. The methods for increase of energy efficiency of CF processes were proposed, in particular, allowing reduction of consumed power and rise of heating [3]. Based on these investigations there was developed a technology of CF welding of the parts with large cross-section (more than 1000 mm^2) and thickness of more than 200 mm. It is successfully used in industry for welding of different thickness parts of low-alloy and high-temperature steels, aluminum alloys.

In the last decade, an urgent and practically significant problem has been producing of high-quality joints of high-strength steels and alloys. For its solution the technologies are required which are distinguished by a high-concentration heating at a minimum energy input [4], including based on CF. Optimizing such processes applicable to specific production cycles is a long, labor-consuming and expensive process, therefore, it is reasonable to use together with it different methods of mathematical and computer modeling of the processes determining weldability of the parts and structure elements.

Such an approach allows significantly expanding a range for searching the optimizing ways in multifactor regulation of welding parameters, effecting, in particular, formation of temperature field.

Aim of the present paper is development of a mathematical model of temperature field kinetics in CF taking into account multifactor effect on heating intensity of high-speed processes of formation and breakdown of single contacts (SC) forming in welding applicable to typical technological cycle of CF of rails.

The mathematical model of heating process in CF is based on modeling of heating of SC forming in interaction of the parts being welded approaching

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Figure 1. Appearance of rail fused surfaces

with set speed ν_{apr}. At their interference in the areas, having microirregularities, there is formation of contacts with heating centers, where metal is melted and local heating of edges of the welded parts takes place. Heating and melting of each SC on the fusion surface provokes formation of deepening-craters generating a relief differing by nonuniform distribution of projections and deepenings (Figure 1).

Figure 2 shows a record of the welding parameters, including values of current and voltage at continuous flashing of rails in a mode accepted in production during welding using K1000 machine. As can be seen from given data at flashing excitation current I_w in the welding circuit rapidly changes its value. The relief determined by area of SC and craters, appearing after their melting [5], is formed in fusion of the several layers of the contact surfaces.

A spark gap Δ_g, having nonconstant value (Figure 3), is formed between the contact surfaces. Amount of contacts simultaneously existing in the flashing process significantly reduces, thus, the total area of the contacts and current passing through them are decreased. An average value of resistance R_c in the contact between the parts and value of current I_w passing through them in flashing are kept at sufficiently stable level (see Figure 2). At that instantaneous current values I_{max} considerably differ form the average indices I_{av}. I_{max}/I_{av} relationship describing stability of the heating process reaches the maximum values in the initial period of process excitation and is stabilized in the final. Also I_{max}/I_{av} value is specifically lower in welding of the parts with lower section thickness. In turn, presence of pulses of welding current rise relatively to its average value is caused by formation of the large area contacts. Indicated dependencies of formation of the large area contacts are related with specifics of flashing appearing in a phenomenon of its self-regulation. Increase of SC area and its conductivity promotes rise of generated in it heat energy that facilitates its melting and reduction of area. However, this condition is fulfilled at unlimited power of source. Under real conditions the value of instantaneous power, generated in the spark gap, is determined by accepted voltage value U_{2xx} and short-circuit resistance of the machine welding circuit that limits a range of change of contact resistance.

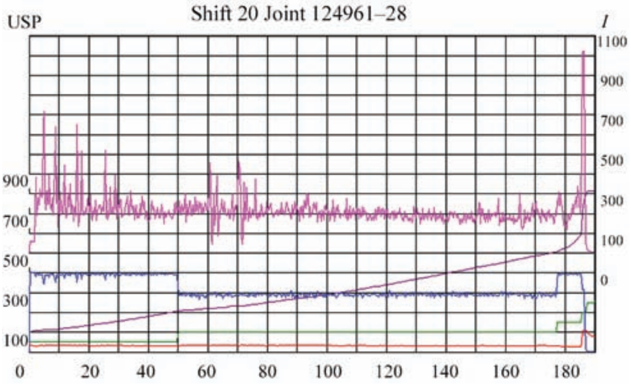

Figure 2. Example of record of the parameters of continuous flash-butt welding process of rails on stationary rail welding machine K1000

Relatively smooth areas are formed in the process of melting of small irregularities on the contact surfaces. This develops the conditions for formation of large area SC. Before the electric contact is formed over the whole area of these surfaces there is filling of the gap between the layers by the metal melt, formed in heating and melting of the contacts on the neighbor areas. Through this melt at sufficiently small gap formation and melting of the separate contacts, area of which is less than possible area of a new contact, are started. Phenomenon of the secondary melting, as it is shown in work [6], has considerably significant effect on heat balance at continuous flashing of the thick-wall parts.

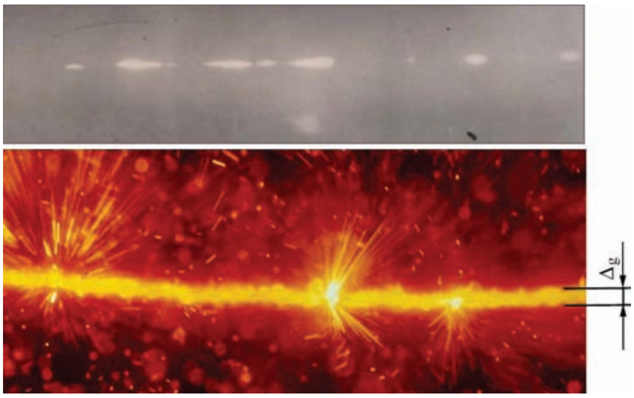

Figure 3. X-ray pattern of spark gap in rail welding

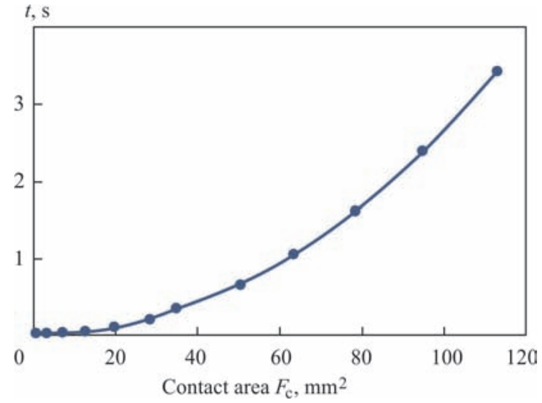

Figure 4. Time of SC existence depending on its area

Value Δ_g is changed in every period of flashing time from 0 to $\Delta_{g\ max}$. Increase of contacts area rises the value of gap forming at their melting, and in this area formation of the new contacts is stopped and total number of simultaneously existing contacts is reduced. Thus, current drops to value $I_{flash.av}$, which is kept at relatively constant level and determined by feed rate in flashing. Therefore, the fusion surface relief is continuously changed, and average value Δ_g is kept on the constant level as the average current in flashing, which is determined by amount of the simultaneously existing contacts. A distinguishing feature of this process is formation of craters of the maximum size. Depth of the craters Δ_g remains the same for each elemental area of the fusion surface. It is determined by thickness of welded parts and voltage U_{2xx}.

As can be seen from Figures 2 and 3, the contacts of different diameters can be formed at the edges of thick-wall parts in process of flashing. The duration of heating of such contacts considerably depends on their area and value of current passing through them (Figure 4). Current value I = 10 kA and temperature T = 1800 °C as a final stage of SC heating were taken for calculation of time of existence of 1–12 mm diameter single contacts with contact area from 0.79 to 133 mm^2. Following from the analysis of fusion surfaces it can be determined that the contacts of 20 to 50 mm^2 area are mostly formed in the flashing process. At that current density in them (Figure 2) is kept in the limits of 200–300 A/mm^2.

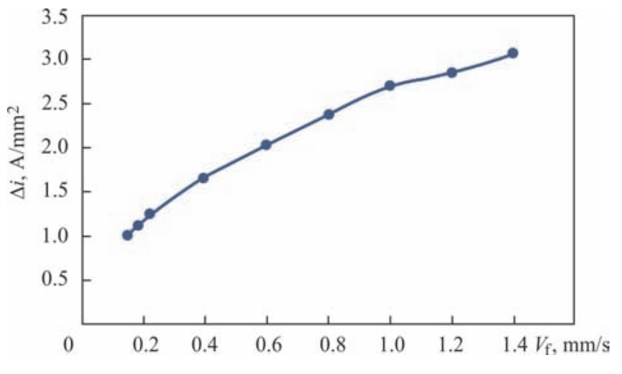

Figure 5. Dependence of value of current density on feed rate of fused surfaces

It was experimentally stated that the average value of current density Δi_w passing through the part in flashing is determined by feed rate (Figure 5) and depends on structure thickness. Rise of v_f provokes increase of Δi_w value at similar feed rates and secondary voltage U_{2xx} applied to the parts, and current density passing in the welding circuit is reduced with increase of part thickness. It is caused by increase of SC area and forming craters after their melting and, respectively, the average value of spark gap Δ_g rises and number of the simultaneously existing contacts reduces. This dependence has linear nature at increase of thickness of welded parts from 5 to 30 mm, whereas, it becomes less apparent at larger thickness of the parts. Therefore, the contacts of 5 and 8 mm diameters have been accepted for selection of typical sizes of simulated SC corresponding to the thicknesses of the parts being welded in 10–30 mm limits, for which CF has the widest application. The total value of current in the secondary welding circuit in CF welding of such part using machines designed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine makes 20–30 kA at 4–7 V voltages.

It was experimentally stated that the duration of SC heating is determined by the area and value of current passing through it. The analysis of current and voltage oscillograms shows that a period of time of contact existence falls at heating in a liquid state accompanied by its melting, boiling with rapid changes of resistance. Therefore, for qualitative and quantitative estimation of the heat balance in addition to the total duration of contact heating t_c it is also reasonable to consider the heating duration in solid phase till melting temperature t_{c1} of its central part at T = = 1550 °C and explosion-forming breakdown at T = = 1800 °C.

In the most of cases there is a gap Δ_g at the contacts boundary, the value of which can very depending on thickness of fused parts. The central part of the contact being heated to the melting temperature represents itself an ellipsoid limited by T_{ml} isotherms. In SC melting the part of liquid melt at the core boundary is kept by surface tension forces and remains on the crater surface after the contact breakdown. The contact being a current conductor in the welding circuit is subjected to effect of the electromagnetic forces creating in it compression and interacting with the powerful electromagnetic field of the welding machine. The compression forces can keep liquid metal in the contact area increasing the duration of its heating. They can also promote its displacement in the spark gap that is observed unders specific flashing conditions [7]. Effect of these forces rises with increase of Δ_g adjacent to the contact area. In the most cases flashing provokes explosion-like breakdown of the SC. It is experimentally determined that temperature of metal outbursted in contact breakdown can vary from 1550 to 1800 °C that corresponds to a core heating temperature. It is also determined that the lower metal temperatures correspond to heating of large area SC (F_c = 50 mm^2) at low voltages U_{2xx} and the extremely high were observed in heating of small contacts accompanied by intensive evaporation. These data make the basis for taking into account in the calculations that the SC central part in heating to T_{ml} temperature will be in a solid state, and its breakdown can start at the temperatures exceeding T_{ml}.

A section of L_x, L_y size (Figure 6) was considered in development of a mathematical model of kinetics of temperature field change $T(x, y, t)$ in the SC area.

Since the main physical mechanism of heat transfer in the considered case is a heat conductivity process, then the kinetics of temperature field is described by the following relationship [8]:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)=c\gamma\frac{\partial T}{\partial t}, \tag{1}$$

where $c\gamma$, λ are the volumetric heat capacity and heat conductivity of material, respectively.

A convective heat exchange with the environment can be described using Newton equation, i.e. boundary conditions for considered problem (1) are the following:

$$\lambda\frac{\partial T}{\partial n}=-\alpha\left(T-T_0\right)+q_s, \tag{2}$$

where n is the normal line to the surface; T_0 is the ambient temperature; α is the coefficient of surface heat emission; q_s is the specific heating power on the contact surface.

An uniform distribution of the ambient temperature T_0 over the whole considered volume was taken as an initial condition:

$$T(x, y, t) = T_0 \text{ at } t = 0. \tag{3}$$

When reaching in the contact place some critical temperature T_{obt}, part of liquid metal was removed (outburst took place).

The solution (1) is based on the finite element method grounded on successive tracing in time with step Δt of temperature distribution in the welded structure. For each tracing step (at the moment of time t) there was a solution of system of algebraic equations obtained as a result of minimization of functional E_T on temperatures in the nodes of finite element partition mesh (Lagrange variation principle):

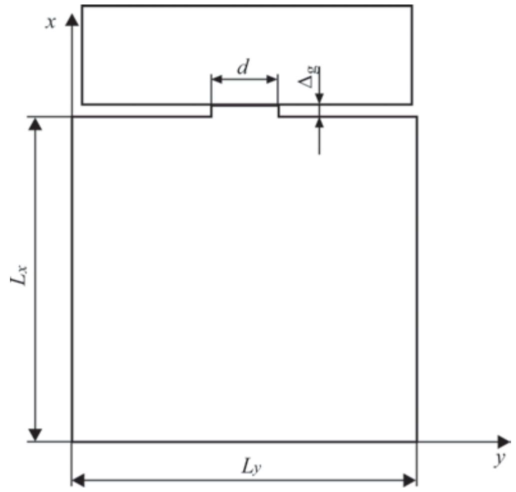

Figure 6. Typical scheme of heating of 5 and 8 mm diameter single contacts

$$E_{\grave{O}}=-\frac{1}{2}\int\limits_S\left[\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)-\right.$$
$$\left.-\frac{c\gamma}{\Delta t}\left(T-T_*\right)\right]dS+\frac{1}{2}\int\limits_\Gamma\left[\alpha\left(T-T_0\right)-q_s\right]d\Gamma, \tag{4}$$

where $T^* = T(x, y, t - \Delta t)$ is the temperature field at the moment $t - \Delta t$; S is the considered total area of section in SC region; G is the outer boundary of calculation area.

Derivatives $\partial T/\partial x$, $\partial T/\partial y$ are expressed for each finite element through the temperatures is the nodes.

Therefore, area integral S is replaced with sum of area finite element integrals ΔS. Minimization of (4) means equality to zero of $\partial E_T/\partial T_{ij}$ derivative, i = = 1, … , M; j = 1, … , N, where M is the number of partition elements on axis 0x, N is the amount of elements on 0y axis.

Figure 7 shows the dependencies of time of existence of different area SCs, from the moment of appearance and to their explosion, on density of the

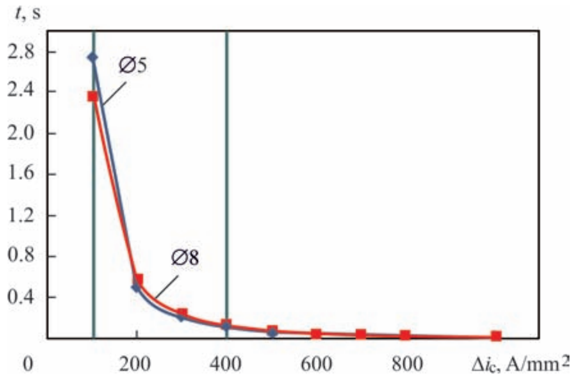

Figure 7. Dependence of time of 5 and 8 mm diameter SC existence on current density Δi_c

passing current. A range of change of Δi_c was selected within the limits of the experimental data given in work [3], temperature of edges of the contacting parts in the initial period of heating $T_0 = 20$°C. Provided data allow making a conclusion on nonlinear effect of the current density on contact existence time, since change of the SC area does not significantly change time of its existence. It can be explained by locality of the heating process before the outburst temperature. Duration of existence of the different area contacts is reduced with rise of the current density. At the current density more than 400 A/mm^2 the duration of contact heating makes centiseconds and breakdown of heated volume is accompanied by intensive vapor formation. At lower current densities there is increase of the contact duration existence that demonstrates larger effect of the heat transfer processes into the edges of the contacting parts and decrease of the heating rate. At the current densities less than 100 A/mm^2 the duration of contacts heating rise so that successive melting of the forming contacts with a set rate of part edges approaching becomes impossible. The melting process turns to resistance heating, at which area of the contacting sections demonstrates progressive increase and propagates along the whole area of the contacting parts. Therefore, values of Δi_c less than 100 A/mm^2 for the indicated welding power sources shall be considered as minimum ones, at which excitation of CF without heating of the part edges is possible. Thus, flashing in current density range 100–400 A/mm at the contacts can be considered the most perspective from point of view of welding heating intensification without additional effect on approaching rate of the parts. It is traditionally used mean for regulation of heating in flashing. Increase of the duration of contacts existence in preservation of their total amount and area results in rise of welding current and termination of melting, transfer of heating into a short-circuit mode. Therefore, a field of current density values, noted in Figure 7, can be determined as the field of unstable flashing in the absence of the system for automatic regulation of resistance in the contact between the parts, in particular, in initial period of flashing, when temperature of part edges is low. For given conditions of contact heating this zone corresponds to current densities 150–200 A/mm^2.

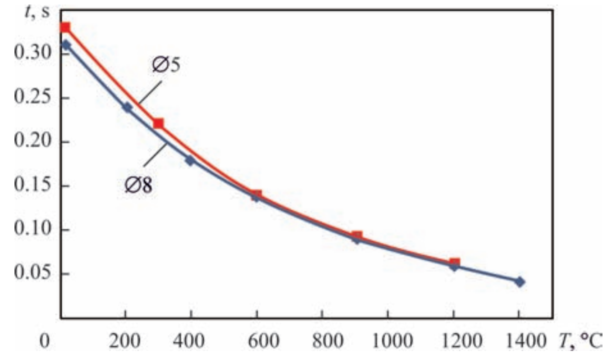

Figure 8. Dependence of time of 5 and 8 mm diameter SC existence on temperature of fused edges

Provided calculation was carried out for the initial conditions of flashing, when unheated edges of the welded parts are in contact. Increase of their temperature changes the conditions of contacts heating and less energy is necessary for their heating, therefore, duration of contacts existence reduces (Figure 8). In heating of part edges to 800–900 °C the range of working current densities in the welding circuit can be reduced from 150 to 200 A/mm^2. This method is successfully used in selection of the optimum programs of voltage decrease in continuous flashing. Program development is based on the principle of flashing at minimum possible voltage in each period of welding. This provides flashing at current densities in a range of 200–300 A/mm^2 and in separate cases at the final period of flashing at 150 A/mm^2 density.

The developed approach can be used for solution of the practical tasks for optimizing the industrial welding cycles, in particular, at estimation of efficiency coefficient of the process. For this it is additionally necessary to estimate heat loss q_{los} in a process of welding. The main mechanisms of heat loss are dissipation of heat energy into environment according to (2) as well as heat content of outbursted liquid metal. i.e.

$$q_{\text{nom}} = V_{\text{obt}} \int_{T_0}^{T_{\text{obt}}} c\gamma dT + \int_t \int_\Gamma \alpha\left(T - T_0\right) d\Gamma dt, \qquad (5)$$

where V_{obt} is the sum outbursted volume of metal.

Thus, the efficiency of heat source η in the process of welding is calculated as

$$\eta = \frac{q_{\text{sour}} - q_{\text{nom}}}{q_{\text{sour}}}, \qquad (6)$$

where $q_{\text{sour}} = \int_t W dt$, W is the heat power of source in the area of single contact, which was taken equal 0.035IU W, that corresponds to observed modes in experimental investigations of temperatures during welding (*I*, *U* are current and voltage supplied on welded structure).

For calculation of time of existence of 5 and 8 mm diameter SC there was taken a current density value of $\Delta i = 250$ A/mm^2 and temperature $T = 1800$ °C as a final heating stage. The heating modes in 100–400 A/mm^2 ranges are of significant interest from point of view of intensification of heating in flashing

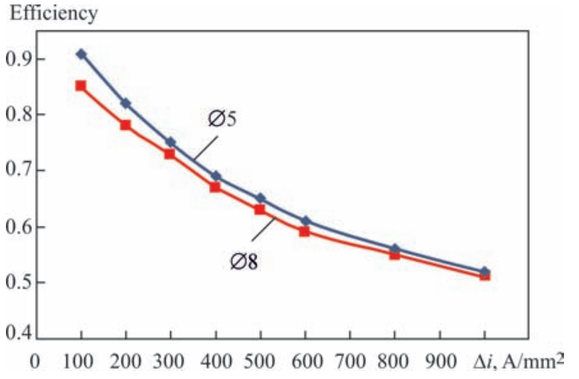

Figure 9. Dependence of thermal efficiency of heating of 5 and 8 mm diameter contacts on Δ*i* passing through SC

since they allow rising welding current and process thermal efficiency. Figure 9 shows the dependencies of thermal efficiency of flashing process according to (6) in variation of current density in the contacts. The highest values of thermal efficiency can be reached in Δi = 100–400 A/mm^2 value range independent on the contact area.

Besides, effect of temperatures of edges being fused on the value of thermal efficiency of welding process was investigated using numerical analysis of temperature distribution in the welding process. For this the SC with passing through it current of 250 A/mm^2 density was considered. As it is shown in Figure 10, increase of temperature of a near-contact metal layer, where SC appears, provokes decrease of thermal efficiency of the process. It is caused by the fact that the energy transferred into the part edges continuously decreases with temperature increase, and lost with melted metal remains constant and even rises. Thermal efficiency in flashing heating respectively reduces.

Obtained results of the numerical analysis of temperature field kinetics in SC area can be used for consideration of a complex of problems on optimizing the specific industrial cycles, in particular, applicable to flash-butt welding of rails. Calculation of the temperature kinetics T in continuous flash-butt welding of rails, the same as for SC, is based on the algorithm of numerical solution of 3D heat conductivity equation in Cartesian coordinate system x, y, z:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)=c\gamma\frac{\partial T}{\partial t}. \tag{7}$$

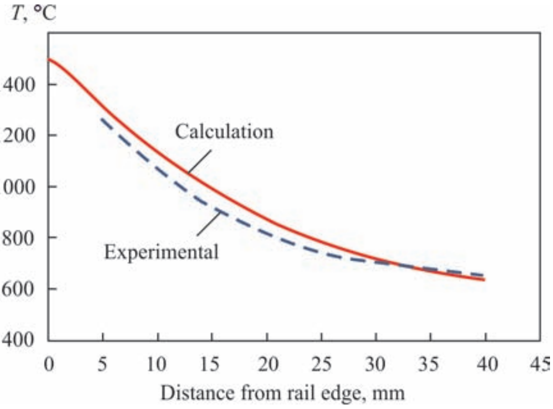

Figure 11. Distribution of temperature along rail axis in continuous flashing

Convective heat exchange with the environment and initial conditions were taken the same as in SC calculation according to relationships (2) and (3). The functional, minimizing of which allows forming the necessary system of linear algebraic equations in scope of finite element solution of heat conductivity problem, for this case will be presented in the next form:

$$\begin{aligned}E_T=-\frac{1}{2}\int_V\Bigg[&\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)-\\&-\frac{c\gamma}{\Delta t}\left(T-T_*\right)\Bigg]dV+\frac{1}{2}\int_\Gamma\left[\alpha\left(T-T_0\right)-q_s\right]d\Gamma,\end{aligned} \tag{8}$$

where V is the considered volume in the welded structure.

The real data, obtained in continuous flash-butt welding of rails on stationary rail welding machine K1000 was used for calculation of the temperature field. Besides, measurement of the temperature field

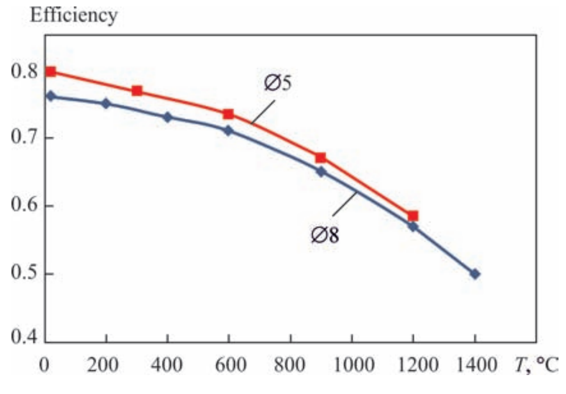

Figure 10. Dependence of thermal efficiency of heating of 5 and 8 mm diameter contacts on temperature of near-contact layer of metal adjacent to fusion surface

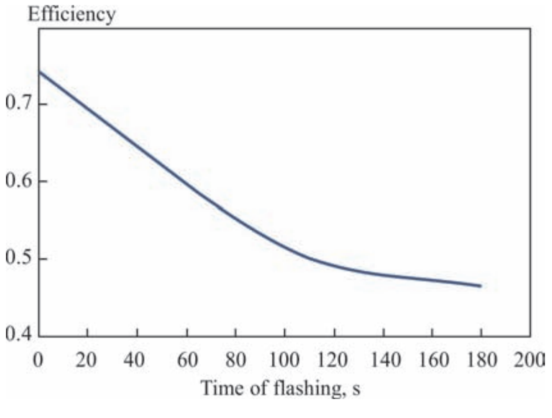

Figure 12. Change of thermal efficiency in process of continuous flashing of rails

using thermocouples was carried out in welding of this joint.

As can be seen from Figure 11, the developed model allows with sufficiently high accuracy predicting the kinetics of temperature field in the considered case that permits its later on application for selection of the optimum temperature modes without performance of expensive experiments. In particular, calculation of efficiency for continuous flashing of rails was carried out based on (6). The results of numerical prediction (Figure 12) show that welding efficiency is sufficiently high in the initial period, but it drops in process of flashing.

It is caused by the fact that the temperature of edges of fused surfaces rises, and thermal efficiency varies as in the case of SC heating (see Figure 10). Application of this model allows significantly expanding the range of searching the ways for intensification of heating in multifactor regulation of the welding parameters, effecting formation of the temperature field as well as make easier search of the optimum thermal cycles in continuous flash-butt welding of thick-wall parts.

Conclusions

1. Analysis of the records of welding parameters and rail fusion surfaces showed that continuous flashing of thick-walled parts can provoke formation of the contacts of different diameters, but their maximum area does not exceed area corresponding to 5 and 8 mm diameter contacts.

2 Duration of heating of different area contacts with continuous flashing depends on the value of current density passing through the contact.

3 There is noticeable dependence of the time of contacts heating on the value of current density in 100–400 A/mm^2 current density range.

4. Increase of temperature of the contact surface provokes significant reduction of the duration of its heating.

5. There were determined the general dependencies of thermal efficiency at continuous flashing on current density passing through the contact, and temperature in the contact zone. It is determined that increase of the current density and temperature of the contact promotes decrease of thermal efficiency.

The temperature field in continuous flash-butt welding of R65 type rails at optimum mode was determined by calculation. The calculation result is close to the experimental one.

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