https://doi.org/10.15407/tpwj2019.11.03

SELF-ORGANIZATION OF THERMAL PROCESSES IN WELDING SHEET LOW-ALLOYED STEEL

R.A. KREKTULEVA, Yu.N. SARAEV, V.M. SEMENCHUK and **R.O. CHEREPANOV**
Institute of Strength Physics and Materials Science of SB RAS
2/4 Akademichesky Ave., 634050, Tomsk, RF

Numerical modeling of thermal processes at weld pool formation in low-alloyed steel under the impact of the electric arc was performed. Different arcing modes are considered. A qualitative difference in propagation and dissipation of thermal energy is found, depending on the modes. Mechanisms of self-organization of thermal structures were studied, which are due to highly nonlinear thermophysical properties of low-alloyed steel, modes of thermal energy feeding into the weld pool and features of its dissipation on the boundaries. The validity of the numerical model is confirmed experimentally, that allows recommending the results of computer studies for practical application. 14 Ref., 7 Figures.

Keywords: *weld, contact zone, heat flow, nonlinearity of thermophysical properties, synergism, self-organization, internal structure*

In keeping with GOST 14771–76, it is recommended to weld sheet low-alloyed steels (of up to 3.5–4.0 mm thickness), widely applied in many branches of industry, using the so-called backing, which is fastened in the lower position of the forming welded joint. The role of backing is to contain the molten metal from flowing out of the weld pool. In technical publications, the notion that application of copper (more seldom aluminium) backing promotes removal of excess heat, due to more intensive dissipation of thermal energy, has become established. That is why it was called heat-removing or forming backing, influencing not only weld metal formation, but also its structure directly in the permanent joint zone [1–3]. The idea of copper backing application outwardly is in good agreement with the theory of self-organization of nonlinear systems, developed by the school of I.R. Prigozhin, winner of 1977 Nobel Prize in chemistry [4]. General concepts of welded joint formation from the standpoint of self-organizing systems are described in [5]. At present the above statement is ever wider applied in development of various systems of automatic regulation of welding and surfacing processes [6–8].

«Self-organization» term in modern scientific language means the process of spatiotemporal structural adjustment of the system that results in the system acquiring new properties, usually, improving its functioning in the former conditions. Three scenarios of self-organization development are possible: order-based order, chaos-based order and order-based chaos, which is also called dynamic chaos. As applied to welding technology, the self-organizing system is the welded joint proper, which was formed not chaotically (melt-solidification in any modes), but taking into account the physical nature of the metal and with strict observation of balance between the inflow of energy to the weld pool and its outflow. The importance of this parameter is shown in [9], where it is established that the rate of the change of molten metal temperature has a dominant influence on the nature of structural-phase transformations in the metal of the weld and HAZ. Correct application of this theory to welding technologies could eliminate many problems of welded joint reliability, particularly their operation under critical conditions: high and low temperatures, higher pressure, etc. Nonetheless, in the majority of the technologies still open are not only the questions of finding the mechanisms, which would bring the technological system in order, but also the issues, associated with the methods of exclusion of behaviour imposed on it, and not characteristic of good governance principles.

The objective of this work is to develop the procedure of numerical analysis of the mechanisms of self-organization of thermal processes in the weld pool in electric arc welding of sheet low-alloyed steel, and experimentally validate it in the case of welding St3 steel, using copper heat-removing backing.

Physical and mathematical statement of the problem. Formulation of research problems follows from consideration of the features of the technology of nonconsumable electrode argon-arc welding. In the weld pool zone, the substance is in four aggregative states: solid, liquid, gaseous and plasma. Different energy conversions proceed simultaneously: electromagnetic, thermal, chemical, mechanical, radiation and intra-atomic. A feature of this welding method consists in that approximately 93–95 % of electric arc energy is consumed for the processes of heat-mass transfer.

The welding process is schematically shown in Figure 1. Welded samples of the same size are placed on a copper backing. The electrode moves along the butt being welded with speed *v* (shown by an arrow). Investigations were conducted for steel samples 60 and 120 mm long, 20 and 40 mm wide, respectively, thickness was varied from 1.2 to 3.5 mm. Dimensions of copper backing along the length were the same as those of the steel samples, or 2 mm longer, thickness varied from 1 to 3 mm with 0.5 mm step. The following width of the gap between the copper backing was set: 0; 1.0; 2.0; 3.0; 4.0; 5.0 and 10.0 mm. A unit on a mobile platform was used to conduct full-scale experiments. The torch with the electrode was fastened in a special holder, with the function of regulation of the extension. The platform started moving at the moment of arc striking. Design of the unit incorporates control of the length of interelectrode gap, volt-ampere characteristics of the power source and speed of welded sample displacement.

In Figure 1 planes A, B and C, crossing the sample perpendicular to the plane of electrode movement, are outlined with the purpose of further theoretical and experimental studies of structural-phase changes of the produced welded joint and checking the adequacy of model representations.

The basics of constructing a mathematical model of technological processes of welding production, including the equations of balance, equation of phase transitions and equation of the kinetics of chemical transformations, are given in work [10]. In keeping with this work, the initial system of equations modeling TIG-welding, has the following form:

$$\rho(T)C_p(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)+ \\ +\frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right); \quad (1)$$

$$L_kV_k=\lambda_s\frac{\partial T}{\partial n_{+0}}-\lambda_l\frac{\partial T}{\partial n_{-0}}; \quad (2)$$

$$q(r)=\frac{\eta I(t)U(t)k}{\pi e^{\left(kr^2\right)}}. \quad (3)$$

In the presented system, equation (1) is the spatial dynamic equation of heat conductivity, (2) is the equation of phase transformations; (3) is the distribution of the plasma arc energy flow density in the zone of the source action.

The system of equations (1)–(3) is complemented by initial conditions

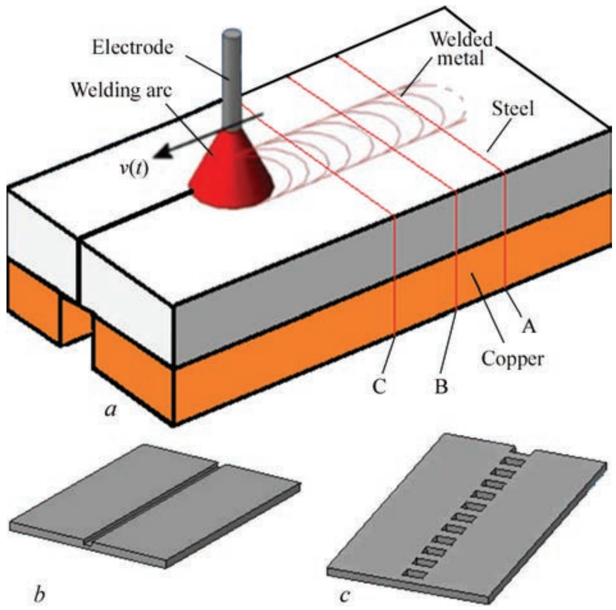


Figure 1. Sketch of welding two steel plates on copper heat-removing backing: *a* — with a gap; *b* — with a groove; *c* — with perforation

$$T(x,y,z,0)=T_0. \quad (4)$$

Boundary conditions are given in the following form:

- outside the region of the source action

$$\lambda\frac{\partial T}{\partial n}=\alpha\left(T-T_0\right)+\varepsilon\left(T_0^4-T^4\right). \quad (5)$$

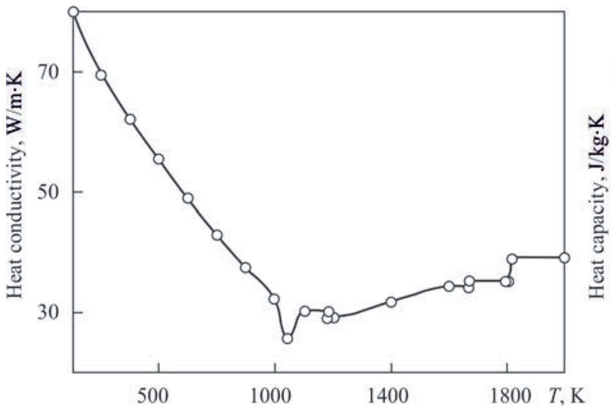
- in the region of the source action

$$-\lambda\frac{\partial T}{\partial n}=\frac{\eta IUk}{\pi}\exp\left(-kr^2\right); \quad (6)$$

- in the region of contact of two dissimilar materials

$$\lambda_1(T)\frac{\partial T_1}{\partial n}=\lambda_2(T)\frac{\partial T_2}{\partial n},\quad x,y,z\in S_{12}. \quad (7)$$

The following designations were used in the system of equations (1)–(7): T — temperature; $\rho(T)$ — dependence of density on temperature; $C_p(T)$ — dependence of heat capacity on temperature; t — time; x, y, z — spatial coordinates; $\lambda(T)$ — dependence of heat conductivity coefficient on temperature; L_k — heat of phase transition (including melting, evaporation, solidification); V_k — speed of movement of phase transition front; n — vector of the normal to the interphase (± indices below indicate different sides from the interphase); λ_s, λ_l — coefficients of material heat conductivity on different sides from phase transition boundary (in particular, solid and liquid phases); r — radius of the heat spot from the burning arc; η and $k(L)$ — semi-empirical parameters, characterized by heat source power and its distribution over the heat



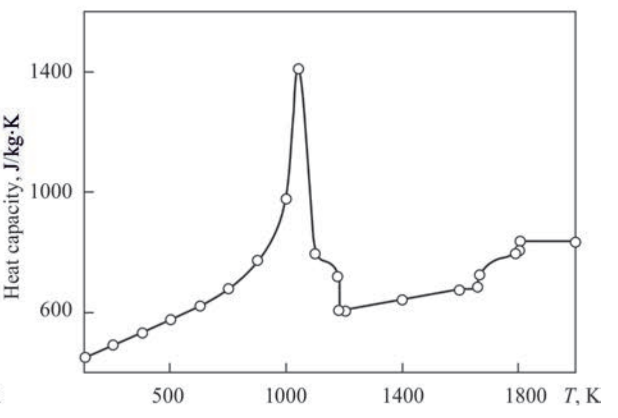


Figure 2. Thermophysical properties of iron and low-alloyed steel

spot; L — length of interelectrode gap; I — current, U — voltage of electric arc source; ε — degree of blackness of the body; $\sigma = 5.669 \cdot 10^{-8}$ W/(m^2·K^4) — the Stephan–Boltzmann constant; α — coefficient of heat exchange with the environment; λ_1, λ_2 — coefficients of heat conductivity of contacting materials; S_{12} — area of contact of dissimilar materials. The burning arc moves along a trajectory determined by the following system of equations:

$$\begin{cases} x = x_0 + V_x t, \\ y = y_0, \end{cases} \tag{8}$$

where x_0, y_0 are the coordinates of the initial point; V_x is the rate of heat source movement along the axis.

Mathematical model (1)–(8) is complemented by experimental dependencies [11] of thermophysical characteristics of low-alloyed steel (Figure 2), and «iron–carbon» constitution diagram [12]. Knowing the detailed temperature distribution in the volume of the samples being welded, the constitution diagram can be used to establish carbon solubility in the respective areas that will help to implicitly allow for the diffusion processes and determine the areas of structural-phase transformations (melting, incomplete melting, overheating, normalizing, etc.) in the weld zone.

The posed problem was solved numerically by the finite difference method [13]. The mesh pitch in different numerical experiments was varied from 0.2 to 0.5 mm, depending on research objectives. Preliminary calculations showed that at correctly selected arcing modes the thermal energy of the source is localized in a narrow strip along the arc movement trajectory. This is attributable to the fact that the coefficient of heat conductivity in the considered steels in the temperature range of 1000–1300 K has a deep minimum, i.e. the rate of heat transfer beyond the boundaries of this range is low. Therefore, it is rational to confine ourselves to study of narrow strips not more than 20 mm wide. It was further established that the temperature field stabilizes along the length at 6 mm distance from the beginning of the welded joint for samples of 1.2 mm thickness. With increase of thickness, this distance gradually increases up to 20 mm for 3.5 mm plates. For further investigation consideration of welded steel plates was limited to dimensions of 60×20×2 mm each.

Given below are the results showing that the considered calculated model allows determination with good accuracy of not just the dimensions of the weld, but also of all the zones of structural-phase transitions in the volume, as a result of multiple thermal «heating-cooling» cycles.

Results of computer experiments on welding steel plates by a moving electric arc. It should be noted that the considered above mathematical formulation of the problem and modern level of computer engineering allow rather accurately (within experimental error of 5–7 %) predicting the arcing modes, that would provide the required characteristics of the weld and HAZ, and, furthermore, additionally derive a large scope of information, which it is impossible to obtain in direct experiments. Application of the techniques of digital visualization allowed tracing in detail all the stages of welded joint formation: heating, melting, evaporation, cooling, condensation, crystallization, phase transitions and thermodeformational changes accompanying them [13]. A systemic approach, developed in [10] was used with this purpose. Six main structural levels were identified, according to which we conducted our research:

- evaluation of the effect of heat source power on distribution of heat flow density in the burning arc flame;
- analysis of the processes of thermal energy distribution in the welded and heat-removing materials;
- determination of all the input parameters of the system, affecting the final properties of the welded joint to varying degrees;
- evaluation of inner structure of welded joint material by the results of computer modeling;

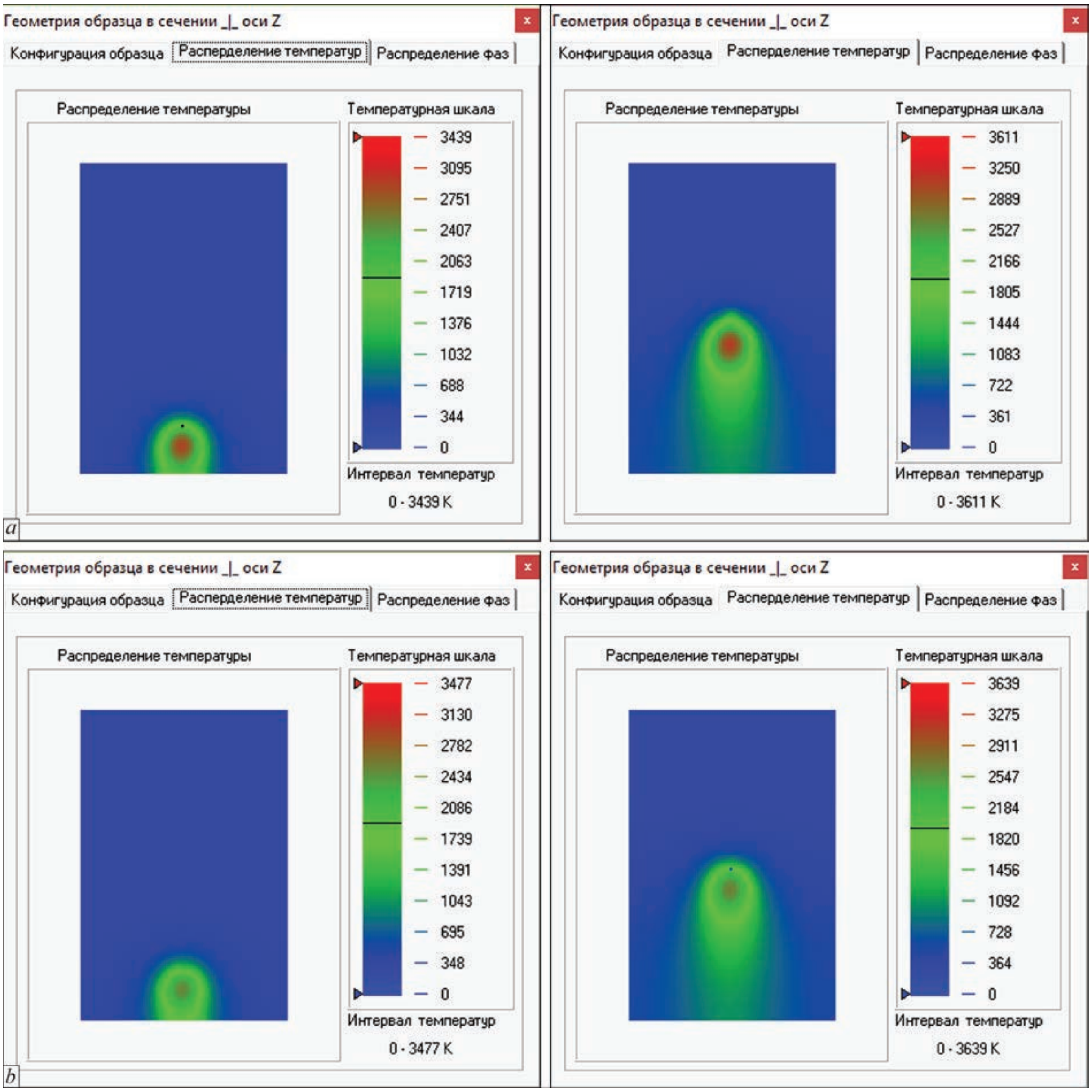


Figure 3. Formation of temperature fields at different moments of time: *a* — on weld pool surface; *b* — same in the zone of contact of welded samples with copper backing

- control of the processes of diffusion and structure formation at the stage of technological process design;
- determination of the criteria of rational self-organization of thermal processes in the welded joint.

The case of welding plates on a backing without a gap was initially considered. Arcing modes were established numerically, which ensured penetration of 2 mm thick plates to the entire depth. Figure 3 shows the temperature fields at two moments of time in two areas: on weld pool surface and in the zone of contact of the welded plates with the continuous copper backing. On the calibration temperature scale the upper value shows the maximum temperature in the sample at the given moment of time, the bar indicates temperature in the zone of contact of the two materials. One can see from the Figures, that as the heat source moves, the maximum temperatures in the zone of arc contact with the steel surface (layer thickness of about 0.2 mm) increase: at the start of the welding process temperature T = 3439 K, and by the middle of the sample T = 3611 K. This is significantly higher than the steel melting temperature (T = 1850 K), whereas in the zone of contact with the copper backing the temperature is close to steel melting temperature. In the selected welding modes an obvious overheating of weld pool surface is observed. Power lowering leads to incomplete penetration. The «heat-removing» backing proper turned out to be the cause for overheating. This was established proceeding from analysis of distribution of contour lines of temperatures in the sample axial section (Figure 4). One can see from the Figure that owing to high heat conductivity of copper the thermal front in it propagates faster than

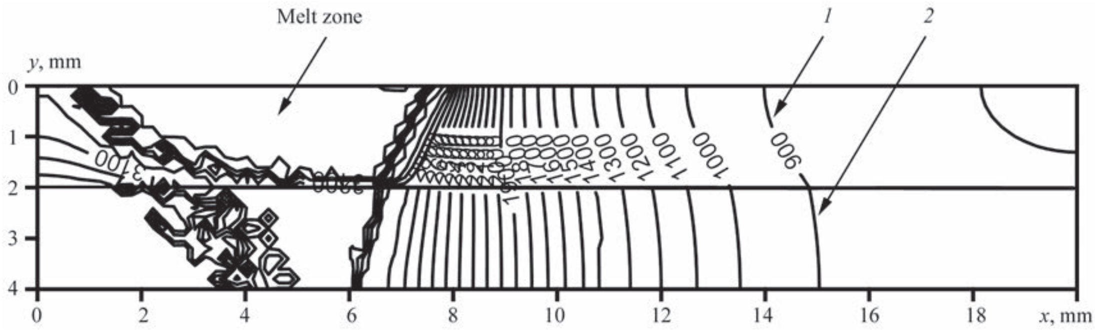


Figure 4. Map of temperature contour lines in the weld pool axial section at the 2nd second from the beginning of welding: *1* — steel butt; *2* — copper backing

in steel. Due to that, part of the energy removed (dissipated) from the pool all the time returns from the backing to the item being welded, heating it from below. From the slope of the contour lines, one can say that initially they run almost parallel to the weld pool walls at a sharp angle to the contact zone. And then in the steel sample the contour lines gradually change their angle of inclination to obtuse one. At removal from the heat source, the bottom of the pool is heated more than its upper part.

This example shows that the main requirements of I.R. Prigozhin theory of self-organization for the welding process have been fulfilled. The nonlinearity of thermophysical properties of steel and increase of thermal energy dissipation through the zone of contact with copper are ensured. Here, an increasing overheating of the weld pool is observed as the burning arc moves forward. It is known from thermodynamics that the system entropy increases with temperature, i.e. the chaotic state of this system is enhanced.

Thus, in the considered case, the third type of self-organization is in place, namely the emergence of chaos from order. The initial structure of welded materials can be regarded as order. It is of interest to study in greater detail the effect of initial geometry of the copper backing in the zone of contact with the weld pool. Four different variants were considered: reduction of the thickness of the continuous backing, formation of a groove under the butt area, formation of the gap and applying perforation.

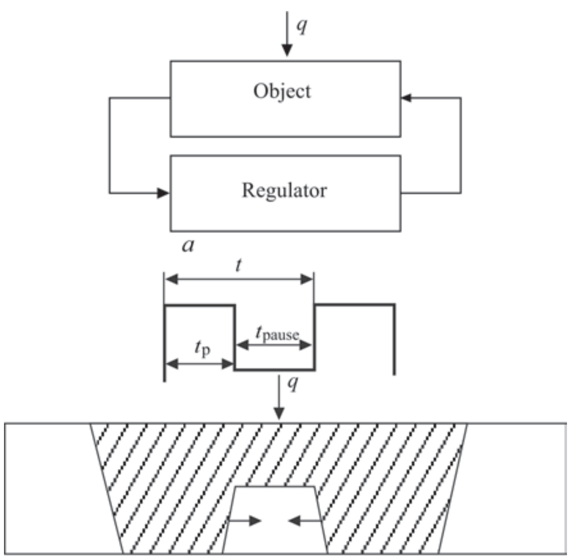


Figure 5. Block-diagram of heat distribution in the weld pool in welding on perforated copper backing and in pulsed-arc welding: t_p — pulse time; t_{pause} — time during the pause and during welding

It should be noted that numerical calculations, conducted using the first two types of backing, showed that in both the cases a noticeable increase of surface temperature was observed along the weld pool length, thus increasing the nonuniformity of the temperature fields, and creating controllable dynamic chaos in the system.

The idea of application of perforated backing (see Figure, 1, *c*) turned out to be more productive. Copper plates of 2 mm thickness were used. Narrow slots of 4×2 mm size were made every 3 mm. Numerical calculations established that surface temperature is practically the same along the entire length of the weld pool, whereas at the weld pool bottom the temperature dependencies are of a pronounced pulsed nature (Figure 5). In this case, the obtained effect is similar to pulsed-arc welding without backing [14]. The difference is only in the fact that at pulsed-arc welding the maximum heat flow is achieved during the pulse, and in direct current welding with application of perforated backing it occurs under the perforation zone. In either case, the temperature inside the weld pool quickly equalizes, self-organization of thermal processes occurs by the type of «new order-based order». Note, however that application of perforated backing in mass production is unprofitable from the economic point of view, as it leads to an increase in technological costs.

The most rational method of self-organization by the type of «new order-based order» can be obtained in welding with application of copper backing with a gap.

During computer experiments the features of welded joint formation for all the types of backing, given above, were studied. Calculation results showed that

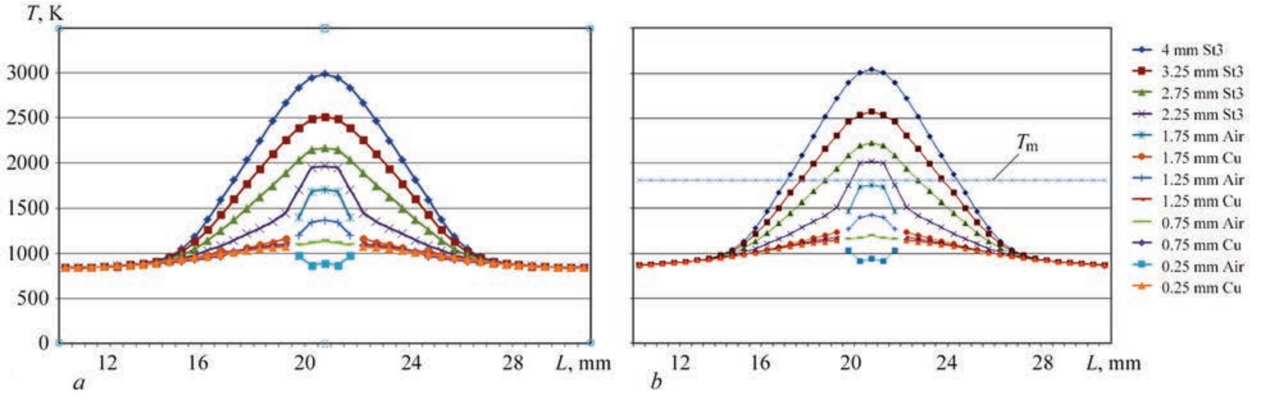


Figure 6. Temperature distribution in the cross-section at the distance of 15 (*a*) and 37.5 mm (*b*) from the beginning of the weld

2 mm backing also with a 2 mm gap turned out to be the most acceptable for welding 2 mm thick plates. We will illustrate it in Figure 6, which shows temperature variation by the width and depth of the welded joint in sections at 15 and 37.5 mm distance from the front end (sections A and C in Figure 1). Similar temperature distributions were obtained in section B (25 mm from the front end), so they are not given by virtue of identity.

These temperature distributions were calculated in the following arcing modes: power W = 1.26 kW, interelectrode spacing d = 1.5 mm, welding speed v = = 2.8 mm/s, width of the gap between copper backing S = 2 mm. In both the graphs the weld dimensions are practically the same in the upper and lower positions. We will explain their determination using the example in Figure 6, *b*, where one more additional horizontal line was drawn, cutting off the melting temperature T = 1850 K on four upper curves, which belong to the steel sample. The other curves belong to the copper backing. The width of the cut off regions is exactly what indicates the dimensions of the weld by depth: from the face side — 7.5 mm, from the reverse side — 2.5 mm that corresponds to normative requirements. The dimensions of these zones can be established similarly from the width of cut-off areas, by measuring on the ordinate axis the temperatures of structural-phase transitions of low-alloyed steels (1523 K — incomplete melting, 1273 K — overheating, 1123 K — normalizing, etc.). Note that by the calculated data the maximum temperatures along the entire length of the melt pool differ by less than 100 degrees. Here, the calculated deviation of weld width is not more than 0.5 mm along the entire sample. Thus, it can be assumed that under these conditions, self-organization of thermal processes by the type of «new order-based order» is ensured. Correct selection of the width of the copper backing gap plays a special role here: narrow gap or its absence lead to excess heating of the weld pool as the electric arc moves, wide gap does not ensure the required heat removal from weld pool bottom and does not protect it from running out (burn-through).

Experimental verification of the validity of calculation results. In order to confirm the correctness of theoretical conclusions and validity of the developed calculation procedure, experimental studies were conducted on a welded joint of low-carbon steel St3sp(killed). Nonconsumable electrode argon-arc welding on a copper backing (with 2 mm gap) was performed, which completely corresponded to the computer experiment. The experiment was conducted at room temperature (T = 300 K) with subsequent cooling of the welded joint in a natural air environment. The experimental set-up was first tested for determination of semi-empirical parameters of the model η and $k(L)$, that yielded the following values: η = = 0.9; $k(L)$ = 8.

It was obtained experimentally that the weld width (directly the fusion zone) in the upper and lower positions coincides with the calculated value with the accuracy of up to 0.5 mm. Metallographic studies were conducted on samples, cut out of the welded plates, located in the following zones: 15, 25 and 37.5 mm from the beginning of the welded joint. Structure of welded joint zones was studied with application of Olympus-GX51 microscope and SIAMS 700 applied

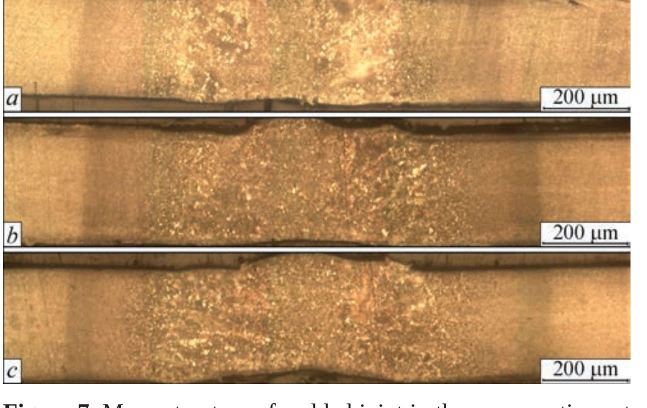


Figure 7. Macrostructure of welded joint in the cross-sections at the following distance: *a* — 15; *b* — 25; *c* — 37.5 mm from the beginning of the welded joint

program package. Characteristic features of welded joint structure are given in Figure 7.

The structure uniformity by welded joint depth and width, both in the area of the weld, and in the zones of structural-phase transitions should be noted. Despite the fact that the weld width is reduced more than 2 times towards the bottom both in calculations and in the experiment, the macrostructure does not reflect it, as its dimensions practically do not change across the thickness.

This is the manifestation of one of the positive qualities of the technology of welding on heat-removing copper backing with a gap. It is, apparently, due to the effect of preheating, realized owing to rapid dissipation of thermal energy from the welding zone and its transfer through the copper backing to lower-lying layers of steel plates. Thus, control of the processes of self-organization of metallographic structures and their ordering across the welded joint thickness take place.

Conclusions

1. Numerical analysis of the dynamics of thermal processes in the weld pool in arc welding of sheet low-alloyed steel was performed, and experimental studies, confirming the validity of numerical calculations and conclusions from their analysis, were conducted.

2. It is found that in case of fulfillment of normative requirements using copper backing, two types of self-organization processes can be in place: new order-based order and dynamically controlled order-based chaos. The second type of self-organization processes has not been discussed in welding publications so far and needs additional study.

3. Mechanisms of self-organization and control of material internal structure were studied, which bring the technological system in order and which allow eliminating the imposed behaviour not inherent to good governance principles.

The work was performed using the funding from RSF 16-19-10010P project, in keeping with 2019 work plan. The authors express their sincere gratitude to Tabanov A.M. for participation in research performance.

1. Kalyuzhny, V.V. (1992) *Copper backing*. USSR Pat. 1745489, Int. Cl. B23K37/06, No. 4799796/08 [in Russian].
2. *Chan Tuan An* (1996) *Formation of weld root in one-sided welding of butt joints using copper backings: Syn. Of Thesis for Cand. of Techn. Sci. Degree.* Kiev [in Russian].
3. Atroshchenko, V.V., Bychkov, V.M., Nikiforov, R.V. et al. (2012) Numerical modeling of penetration shape in consumable electrode argon-arc welding on copper backing. *Vestnik Ufimskogo GATU*, **16**, 53(**8**), 89–93 [in Russian].
4. Nikolis, G., Prigogine, I. (1977) *Self-organization in Non-equilibrium systems*: From dissipative structures to order through fluctuations. New York, John Wiley.
5. Zuev, I.V., Galkin, A.G., Bushma, V.O. (1995) Self-organisation in certain processes of welding and processing materials. *J. of Advanced Materials*, B2, 70–74.
6. Saraev, Yu.N., Lunev, A.G., Kiselev, A.S. et al. (2018) Complex for investigation of arc welding processes. *The Paton Welding J*., **8**, 13–21.
7. Lebedev, V.A. (2015) Mechanized and automatic synergic welding with pulsed electrode wire feed. *Welding Int*., 29(**2**), 140–144.
8. Starke, G., Hahn, D., Diana G. et al. (2016) Self-organizatiom and self-coordination in welding automation with collaborating teams of industrial robots. *Machines*, **4**, 23.
9. Efimenko, L.A., Ramus, A.A., Merkulova, A.O. (2015) Peculiarities of austenite decomposition in heat-affected zone in welding of high-strength steels. *Fizika Metallov i Metallovedenie*, 116(**5**), 520–529 in Russian].
10. Krektuleva, R.A., Bezginov, R.O., Cherepanov, O.I., Cherepanov, R.O. (2015) Investigation of thermophysical processes in contacting pair of materials St3-Al in consumable electrode argon-arc welding. *Fizicheskaya Mezomekhanika*, 18(**3**), 92–100 [in Russian].
11. Zinoviev, V.E. (1989) *Thermophysical properties of metals at high temperatures*: Refer. Book. Moscow, Metallurgiya [in Russian].
12. Lyakishev, N.P. (1996) *State diagrams of binary metallic systems*: Refer. Book. In: 3 Vol. Vol. 1. Ed. by N.P. Lyakishev. Moscow, Mashinostroenie [in Russian].
13. Krektuleva, R.A., Cherepanov, O.I., Cherepanov, R.O. (2017) Numerical investigation of residual thermal stresses in welded joints of the heterogeneous steels with account of technological features of multipass welding. *Applied Mathemathical Modelling*, **42**, 244–256.
14. Bezhin, O.N., Kosyakov, V.A., Krektuleva, R.A. (1998) Formation of thermal localized structures in the weld during consumable electrode pulsed-arc welding. *PMTF*, 39, 232(**6**), 172–177 [in Russian].

Received 08.07.2019