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OPTIMUM LOCATION OF THE REGIONS OF HEATING AND COOLING UNDER HEAT TREATMENT OF WELDED PLATES

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For movable circular regions of heating and cooling with respect to a weld in a plate, a method is proposed for determining their optimum location such that residual stresses decrease most effectively. We use a solution of the problem of thermoelasticity for an infinite plate on its heating by a heat flux described by a Gaussian distribution. On the basis of the Tresca–Saint-Venant yield condition, nomograms which make it possible to determine the distances of the centers of regions of heating to the center line of the weld are constructed.

In the modern technology of thermal treatment, tempering is a method most extensively used for the reduction of residual stresses in metallic structures [1]. However, it is not suitable for large objects. Furthermore, at high temperatures, welded structures with closed welds, quenched structures, and inhomogeneous (as to thermophysical and mechanical properties) structures cannot be tempered. In these cases, local thermal treatment is used. The most promising is local thermal treatment with movable sources of heat parallel to welds. The effectiveness of this treatment depends substantially on the location of the sources of heat relative to the weld. The nomograms presented below enable one to determine the optimum distances of movable circular regions of heating and cooling to the weld.

Consider a large welded plate with circular regions of heating and cooling which move with a constant rate v. Let us designate the distances of the centers of the regions of heating and cooling to the center line of the weld by a and b (Fig. 1). Assume that the temperature field and stresses at infinity tend to zero since the plate is large, its thermophysical and mechanical properties do not depend on temperature, the heating regime is steady in the Oxy coordinate system, which moves together with the regions of heating and cooling, and that the center line of the weld coincides with the Ox axis (Fig. 1).

It is known that longitudinal residual stresses σ_{xx}^0 after welding of thin-walled structures are tensile, as a rule [1], and far exceed transverse stresses σ_{yy}^0 in the weld zone. In this case, it follows from the Tresca–Saint-Venant condition that the optimum distances a_0 and b_0 should be chosen so that the difference between the longitudinal σ_{xx}^t and transverse temperature stresses σ_{yy}^t in the weld zone (at $y = 0$) is positive and as large as possible. Then plastic elongation deformations, which reduce both plastic shortening deformations caused by welding and, respectively, residual stresses, will arise in those zones of the weld for which the sum of the values $\sigma^0 = \sigma_{xx}^0 - \sigma_{yy}^0$ and $\sigma^t = \sigma_{xx}^t - \sigma_{yy}^t$ attains the yield limit.

Let us determine the parameter σ^t in the case of heating with gas burners whose specific thermal flux along the radius of the region of heating is described approximately by a Gaussian distribution [3]:

$$q = q_0 \exp(-k_* r^2), \qquad (1)$$

where q_0 is the largest thermal flux in the center of the region of heating, k_* is the heating concentration factor, and r is the distance from the center. For this purpose, we use the solution (which was published previously [4]) of a nonstationary problem of thermoelasticity for an infinite plate under its two-side heating by law (1). Let the plate be heated with two regions of heating which are symmetric about the weld with centers at points $(0, \pm y_0)$. Then the difference of temperature stresses on the center line of the weld is determined by the following formula:

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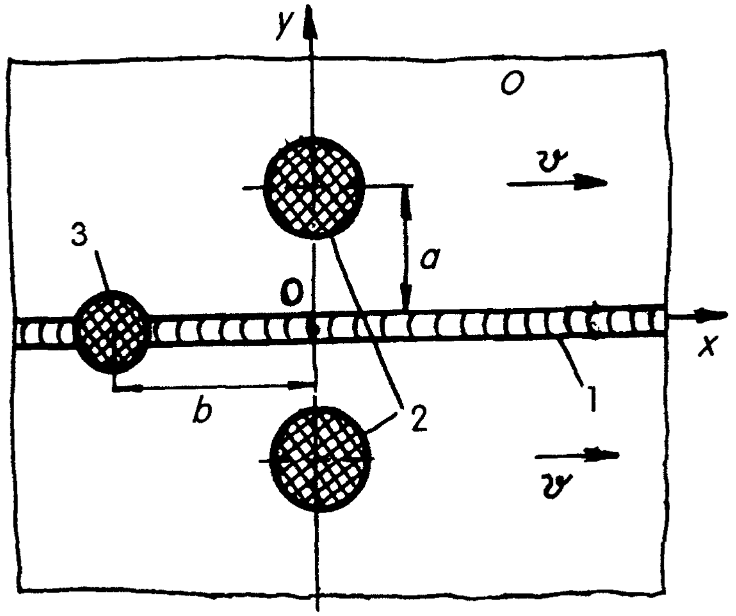

Fig. 1. Scheme of thermal treatment of a plate with weld: (1) weld; (2) heating zones; (3) cooling zone.

$$\sigma'(\xi, \eta_0) = A \int_0^{\infty} \left[\left(\frac{\bar{\rho}^2}{\tau + \gamma} + 2\frac{\bar{\rho}^2}{\rho^2} \right) E_1 - 2\frac{\bar{\rho}^2}{\rho^2} \right] \frac{E_2}{\rho^2} d\tau, \qquad (2)$$

where

$$A = \frac{q_0 E \alpha_t}{2k_*}, \quad E_1 = \exp\left[-\frac{\rho^2}{2(\tau + \gamma)} \right], \quad E_2 = \exp(-\beta\tau), \quad \rho^2 = (\xi + \tau)^2 + \eta_0^2,$$

$$\bar{\rho}^2 = (\xi + \tau)^2 - \eta_0^2, \quad \gamma = \frac{v^2 r_*^2}{8a_*}, \quad \beta = 4\frac{\alpha a_*}{\lambda v^2 h}, \quad \xi = \omega x, \quad \eta_0 = \omega y_0, \quad \omega = \frac{v}{2a_*},$$

E is Young's modulus, α_t, λ, a_*, and α are, respectively, the linear thermal expansion coefficient, coefficient of thermal conductivity, coefficient of thermal diffusivity, and coefficient of heat transfer, h is the thickness of the plate, r_* is the radius of the region of heating, and ξ, η_0 are dimensionless coordinates.

Therefore, the problem of determination of the optimum distance a_0 reduces to the search for the values of the variables $\xi = \xi_*$ and $\eta_0 = \eta_*$ for which the value σ' will be largest. Formula (2) implies that ξ_* and η_* depend only on the dimensionless parameters β and γ and allows one to calculate the value η_* for different β and γ (Fig. 2).

By using the presented nomograms, the optimum distances a_0 were determined in the following way. On the basis of given values of a_*, λ, α, h, v, and r_*, we calculated the parameters γ, β, and ω. Then we found the value η_* from the nomograms and further calculated

$$a_0 = \frac{\eta_*}{\omega}.$$

Choosing the region of cooling, we consider the results in [2]. It was shown there that the maximum value of σ' originating from regions of cooling which move along the prescribed line is attained in front of it. Calculations performed with formula (2) for all values of β and γ show that the parameter $\xi_* < 0$. This means that the value of σ^t is largest in the weld zone on heating behind the line which joins the centers of the regions of heating. To attain the maximum value of σ^t on heating simultaneously with additional cooling, the region of cooling must be located on the weld behind the line which joins the regions of heating at a certain optimum distance b_0 from it (see Fig. 1). When the sources of cooling are distributed along a circle of radius r_0, the optimum distance $b_0 \approx 2r_0$.

To prevent the appearance of new plastic deformations and residual stresses in zones being heated, the maximum temperature of the plate must satisfy the following additional condition:

$$T = T_0 = \frac{2\sigma_y}{E\alpha_t},$$

where σ_y is the plastic limit of the material. Therefore, the largest thermal flux q_0 in the center of the region of heating is chosen so that

$$T \le \frac{2\sigma_y}{E\alpha_t}.$$

Example. Assume that we intend to reduce residual tensile stresses in a welded plate with thickness $h = 0.01$ m. The plate is made of 09G2S steel, $E = 210$ GPa, $\alpha_t = 13.5 \cdot 10^{-6}\,\mathrm{deg}^{-1}$, $\sigma_y = 300$ MPa, $a_* = 13 \cdot 10^{-6}\,\mathrm{m}^2/\mathrm{sec}$, and $\lambda = 41.6\,\mathrm{W/(m \cdot deg)}$. For heating and cooling, we use the circular regions of radius $r_* = r_0 = 0.02$ m which move with rate $v = 0.005$ m/sec. The conditions of heat exchange with the environment are characterized by the coefficient of heat transfer $\alpha = 832\,\mathrm{W/(m^2 \cdot deg)}$.

First, we determine a_0, b_0, and T_0 by substituting the values of a_*, λ, α, h, v, and r_* in formula (2) and evaluating the parameters ω, β, and γ. As a result, we obtain $\omega = 192.3\,\mathrm{m}^{-1}$, $\beta = 0.054$, and $\gamma = 7.4$. From Fig. 2, we find $\eta_* = 8$. Hence, we have

$$a_0 = \frac{\eta_*}{\omega} = 0.042\ \mathrm{m}.$$

Then, starting from the values of r_0, E, α_t, and σ_y, we determine $b_0 = 0.04$ m and $T_0 = 212°$C.

Thus, we should locate the centers of the regions of heating at a distance $a_0 = 0.042$ m from the center line of the weld. The centers of the regions of cooling are positioned behind the line which joins the centers of the regions of heating at a distance $b_0 = 0.04$ m from it. The temperature of the zones of heating must not exceed $T_0 = 212°$C.

To reduce residual stresses from welding by the scheme proposed in Fig. 2, we studied experimentally three plates of $0.6 \times 0.3 \times 0.012$ m made of VSt3sp steel. Residual stresses in each of them were generated by welding on a bead in the middle of the plates in the longitudinal direction. Preliminarily, the plates were annealed to eliminate residual stresses that could be generated in the course of their manufacturing. Each plate was heat treated with movable acetylene-oxygen burners located symmetrically about the weld (bead). For the purpose of cooling the weld (if required) with liquid or gas, a hose was connected to the rear of the burners.

Temperature was measured with wire chromel-alumel thermocouples (the wire was 0.3 mm in diameter) caulked in to a depth of 0.006 m. Longitudinal residual stresses in a plate which was not heat treated and in two others after heating were determined by a mechanical method by cutting the plates into strips. The strains arising were measured by KF5PI–5–100–5–12 strain gauges glued on two sides of each plate.

Welds of the plates were heat treated at $v = 0.0042$ m/sec, $r_* = r_0 = 15$ mm, $a = 50$ mm, and $b = 50$ mm with further cooling with water. The maximum temperature in the middle sections of the plates was as high as 242°C.

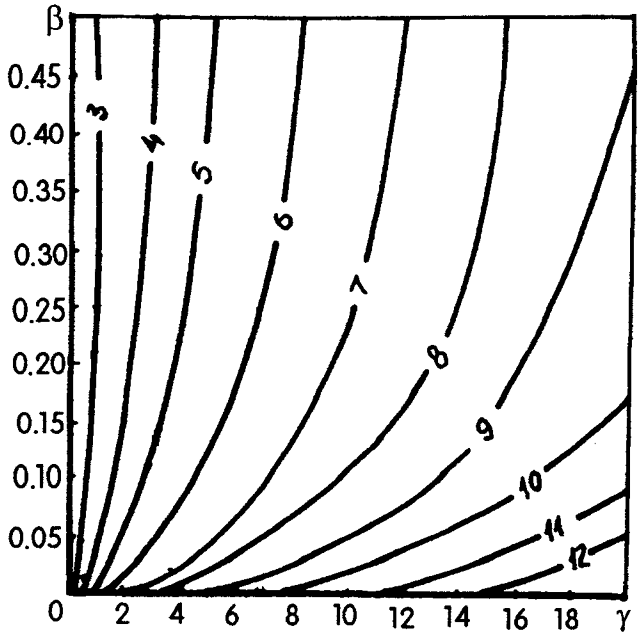

Fig. 2. Nomograms for determination of η_*.

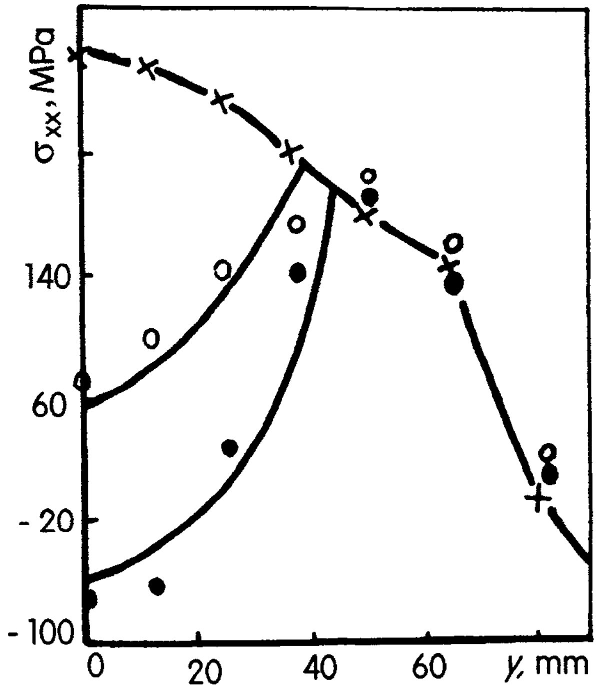

Fig. 3. Distribution of longitudinal residual stresses σ^0_{xx}: × before thermal treatment; ○ after thermal treatment without additional cooling of a weld; ● after thermal treatment with additional cooling.

The results of the experimental studies of longitudinal residual stresses σ^0_{xx} near the weld are presented in Fig. 3. Additional investigations performed at other values of the distances a and b showed that the residual stresses σ^0_{xx} decreased to a smaller degree.

Thus, by additional cooling of a weld simultaneously with its heating, one can not only completely eliminate residual tensile stresses but generate residual compression stresses.

CONCLUSIONS

The proposed method enables one to control residual stresses in the zone of welded joints in a sufficiently wide range with generation (if necessary) of residual compression stresses in the weld. By applying the method, one can improve greatly the endurance of welded joints and decrease substantially the consumption of energy, especially for sheet and shell-like structures with long welds, for which any simultaneous heating is impossible under working conditions.

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