MODELLING OF A TEMPORARY TEMPERATURE FIELD DURING ARC WELD SURFACING OF STEEL ELEMENTS TAKING INTO ACCOUNT HEAT OF THE WELD

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Abstract. In this work, a model of a temperature field in a steel element during a single-pass arc weld surfacing is presented. Analytical solution for half-infinite body model is obtained by aggregating temperature increments caused by applying liquid metal and heat radiation of a moving electrode. The assumptions are Gaussian distributed heat sources of applied metal and the weld and of an electric arc heat source. Computations of the temperature field were carried out during arc weld surfacing of cuboidal steel element. The results are presented as temporary and maximum temperature distribution in the element's cross-section and thermal cycles at selected points. The accuracy of the solution is verified comparing a calculated fusion line to that obtained experimentally.

Keywords: *modeling, arc weld surfacing, temperature field*

Introduction

In the modeling of a temperature field of welding processes, a single-distributed heat source model is generally assumed, reflecting the direct impact of the electric arc on the surfacing object. This approach is found in the description of the temperature field during welding processes using analytical and numerical methods [1-7]. The shape of the fusion lines during arc weld surfacing exhibit shape irregularity, which is difficult to restore by means of the description of the temperature field obtained by using the analytical method and the single-distributed heat source model.

Jeong and Cho [8] proposed taking into account the area of melted metal in fillet weld by summing up a bivariate Gaussian distributed heat source. Analogically, Kang and Cho [9] solved the temperature field in the welding model using GTA (Gas Tungsten Arc) method taking into consideration filler wire.

Arc weld surfacing is distinguished by applying liquid metal (in some cases up to 20 millimeters thick), which spills across the surface and constitutes an addition-

al heat source. Analyses of metallographic specimens of surfaced elements [10] indicate that fusion lines have more irregular shapes than in the case of welding, due to liquid metal spilling across the surface of the welded element. The necessity of taking into consideration the heat of melted metal in temperature field solutions in arc weld surfacing processes is therefore essential, which is presented in this work.

1. Analytical solution of temperature field during arc weld surfacing

The description of the temperature field is summing temperature fields caused by the heat of direct impact of an electric arc and the heat transferred to the surfaced object through the molten electrode material This allows the formulation of the temperature field in the form:

$$T(x,y,z,t) - T_0 = \sum_{i=1}^{2} \Delta T_i \tag{1}$$

where: ΔT_1 and ΔT_2 are temperature accruals caused by the heat of liquid metal of weld and electric arc respectively.

The analytical description of the above-mentioned field is obtained using the heat conduction equation in a fixed Cartesians coordinate system (x, y, z):

$$\nabla(\lambda \nabla T) + q = C_p \rho \frac{\partial T}{\partial t} \tag{2}$$

where: C_p - specific heat [J/kg K], ρ - density [kg/m^3], λ - coefficient of heat conduction [W/m K]), T - temperature, t - time,
which for infinite body with temporary heat source q applied at arbitrary point of body with coordinates (x', y', z') takes the following form [11]:

$$T(x,y,z,t) = \frac{q}{C_p \rho (4\pi a t)^{1.5}} \exp\left(-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4at}\right) \tag{3}$$

with the following conditions:

$$T(x,y,z,0) = T_0$$

$$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = 0 \ \text{ for } \ x, y \to \pm\infty$$

$$\frac{\partial T}{\partial z} = 0 \ \text{ for } \ z \to \pm\infty$$

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0$$

where a - thermal diffusivity [m^2/s].

Based on this solution for point source and solutions for planar source [12], an analytical description of temperature field in semi-infinite body for singular volumetric heat source (Fig. 1) was formulated in the works [13, 14].
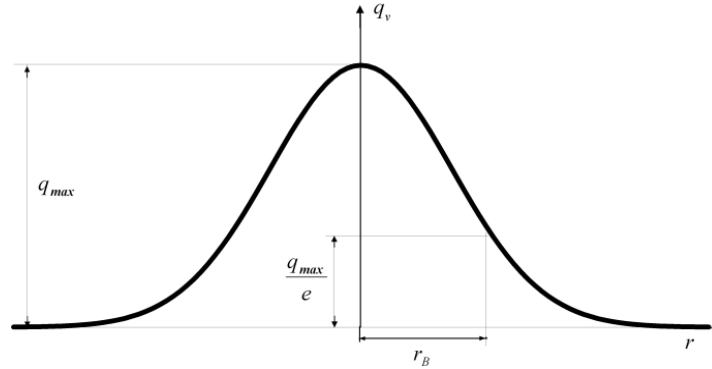

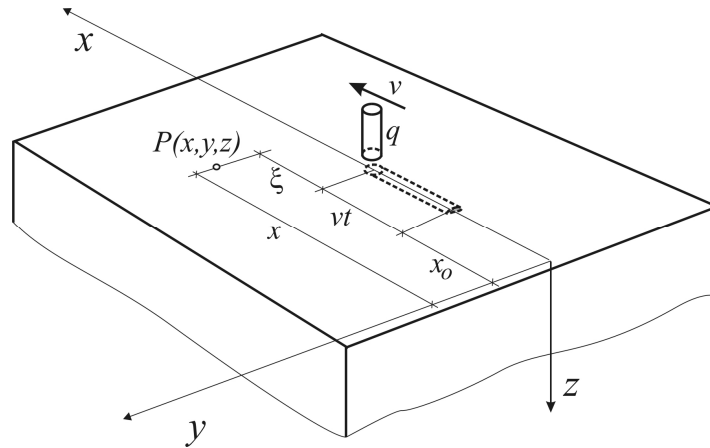Fig. 1. Gaussian distribution of volumetric heat source

Fig. 2. The scheme of single-pass surfacing

According to that solution and Eq. (2) increase of temperature at point P with coordinates (x, y, z) ξ meters away from source (Fig. 2) can be described by:
- for time $t \leq t_c$, where t_c means total time of creating the weld:

$$\Delta T_i = A_i^H \int_0^t F_i^H \left(t''\right) dt''$$ (4)

- for time $t > t_c$:

$$\Delta T_i = A_i^C \int_0^{t_c} F_i^C \left(t'\right) dt'$$ (5)

where:

$$A_i^H = \frac{3}{16} \frac{\dot{q}_i}{C_p \rho \pi a z_{0i}} \exp\left(-\frac{v\xi}{2a} - \frac{v^2 t_{0i}}{4a}\right) \tag{6}$$

$$A_i^C = \frac{3}{16} \frac{\dot{q}_i}{C_p \rho \pi a z_{0i}} \tag{7}$$

$$
\begin{aligned}
F_C(t') = &\frac{1}{t + t_{0i} - t'} \exp\left(-\frac{(x - v\,t' - x_0)^2 + (y - y_0)^2}{4a(t + t_{0i} - t')}\right) \\
&\left\{\left(\left(1 - \frac{z^2 + 2a(t - t')}{z_{0i}^2}\right) erf\left(\frac{z + z_{0i}}{2(a(t - t'))^{0.5}}\right) + \right.\right. \\
&\left. -\Phi(z) erf\left(\Phi(z)\frac{z - z_{0i}}{2(a(t - t'))^{0.5}}\right)\right) + \\
&+\frac{4a(t - t')}{z_{0i}^2}\left(\frac{z + z_{0i}}{2(\pi a(t - t'))^{0.5}} \exp\left(-\frac{(z - z_{0i})^2}{4a(t - t')}\right) + \right. \\
&\left.\left. -\frac{z - z_{0i}}{2(\pi a(t - t'))^{0.5}} \exp\left(-\frac{(z + z_{0i})^2}{4a(t - t')}\right)\right)\right\}
\end{aligned}
\tag{8}
$$

$$
\begin{aligned}
F_H(t'') = &\frac{1}{t'' + t_{0i}} \exp\left(-\frac{\xi^2}{4a(t'' + t_{0i})} - \frac{v^2 t''}{4a}\right)\left\{\left(1 - \frac{z^2 + 2at''}{z_{0i}^2}\right)\left(erf\left(\frac{z + z_{0i}}{2(at'')^{0.5}}\right) + \right.\right. \\
&\left.-\Phi(z) erf\left(\Phi(z)\frac{z - z_{0i}}{2(at'')^{0.5}}\right)\right) + \frac{4at''}{z_{0i}^2}\left(\frac{z + z_{0i}}{2(\pi at'')^{0.5}} \exp\left(-\frac{(z - z_{0i})^2}{4at''}\right)\right. \\
&\left.\left.-\frac{z - z_{0i}}{2(\pi at'')^{0.5}} \exp\left(-\frac{(z + z_{0i})^2}{4at''}\right)\right)\right\} dt''
\end{aligned}
\tag{9}
$$

$$\Phi(z) = \begin{cases} -1 & for\ \ z \in\ <0, z_{0i}> \\ 1 & for\ \ z \in (z_{0i}, \infty) \end{cases} \tag{10}$$

$$\dot{q}_2 = \eta U I - \dot{q}_1 \tag{11}$$

$$t_c = l/v \tag{12}$$

$$\xi = x - v(t + t_0) - x_0 \tag{13}$$

U, I and η voltage, amperage and arc efficiency respectively, l length of the weld, and v welding velocity (of electrode), indices i by sources' parameters concern (for $i = 1$) the heat accumulated in applied weld and (for $i = 2$) remaining heat determined by Eq. (11), z_{0i} denotes depth of heat source depositions, while quantity t_{0i} characterizes the surface heat distribution, so that:

$$r_i^2 = 4at_{0i} \tag{14}$$

where r_i denotes averaged radiuses of Gaussian distributed heat sources [15].

The total amount of heat q_1 contained in the material of melted electrode is expressed by relationship [16]:

$$q_1 = \Delta q_{solid} + \Delta q_f + \Delta q_{liqiud} \tag{15}$$

where:

Δq_{solid} - heat necessary to heatup the electrode from initial temperature to melting temperature

$$\Delta q_{solid} = mC_p\left(T_S - T_e\right) \tag{16}$$

Δq_f - heat used for melting the electrode (heat of fusion)

$$\Delta q_f = mL \tag{17}$$

Δq_{liquid} - heat used for heatingup melted material to the temperature in which the drop of metal falls on the surface of welded material

$$\Delta q_{liquid} = mC_p\left(T_L - T_S\right) \tag{18}$$

Then Eq. (15) is:

$$q_1 = mC_p\left(T_S - T_e\right) + mC_p\left(T_L - T_S\right) + mL \tag{19}$$

The initial temperature of electrode T_e from the welding head is set at 373 K. On account of this and differentiating Eq. (19) with respect to time:

$$\dot{q}_1 = \dot{m}\left(C_p\left(T_L - T_e\right) + L\right) \tag{20}$$

where:

$$\dot{m} = \rho_e \frac{\pi d^2}{4} v_e \tag{21}$$

v_e [m/s] - velocity of passing electrode wire with diameter d [m] and density ρ_e [kg/m^3], T_L - temperature of liquid metal applied on welded surface [K] and T_S - solidus temperature [K].

The face of weld is determined mainly by surface tension forces. Based on experimental researches, Hrabe et al. [17] proposed the parabolic shape of the face of weld, which has been applied in this work.

2. Example of computations

Computations of time- and spatially-varying changeable temperature field for steel element in a shape of side of length 0.4 m and width 0.4 m made from steel S235 have been conducted. The calculations were performed using the authorial program created in the Borland Delphi environment. Thermal properties of welded subject material and an electrode have been determined by $a = 8 \cdot 10^{-6}$ m^2/s , $C_p =$ = 670 J/kg K, $\rho = 7800$ kg/m^3, $L = 268$ kJ/kg and $T_S = 1766$ K.

Numerical simulations of temperature field have been made while applying weld 0.2 m long in the middle part of the plate (initial coordinate of weld $x_0 =$ = 0.1 m). The volumetric heat sources with Gaussian distribution of power density distinguished by $z_{01} = 0.0005$ m, $t_{01} = 4.5$ s and $z_{02} = 0.009$ m, $t_{02} = 0.1$ s. The sum of heat powers corresponds to welding parameters ($U = 24.3$ V, $I = 232$ A, $\eta = 0.6$) used in welding trials using GMA (Gas Metal Arc) method conducted by Klimpel et al. [10]. Likewise in the experiment, in calculations were assumed welding velocity $v = 0.007$ m/s, electrode wire diameter $d = 1.2$ m, wire feed speed $v_e =$ = 0.013 m/s and bead dimensions $h_w = 2.77$ mm and $w_w = 11.93$ mm. The initial temperature of liquid metal applied on the surface of cast was assumed at $T_L =$ = 2773 K.

The analysis of the temperature field in middle cross-section of surfaced steel cast has been conducted. In Figures 3-6 temperature distributions are presented during surfacing: 0.5 s before (Fig. 3) and 0.5 s (Fig. 4), and 4 s (Fig. 5) after passage of electrode and application of weld.
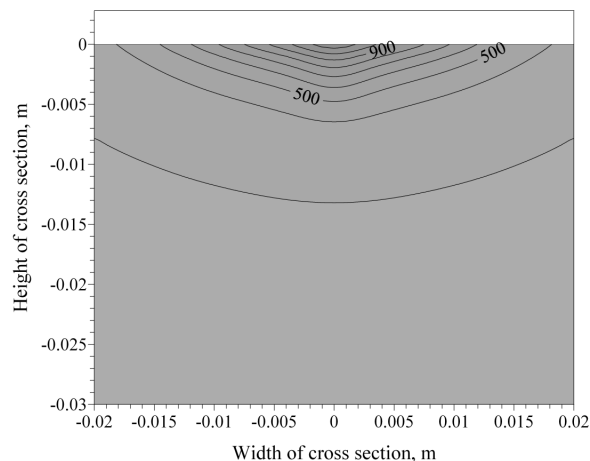

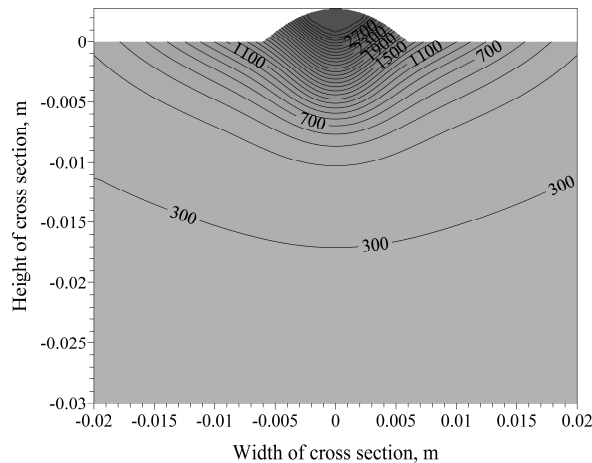Fig. 3. Temperature field 0.5 s before the passage of electrode

Fig. 4. Temperature field 0.5 s after the passage of electrode
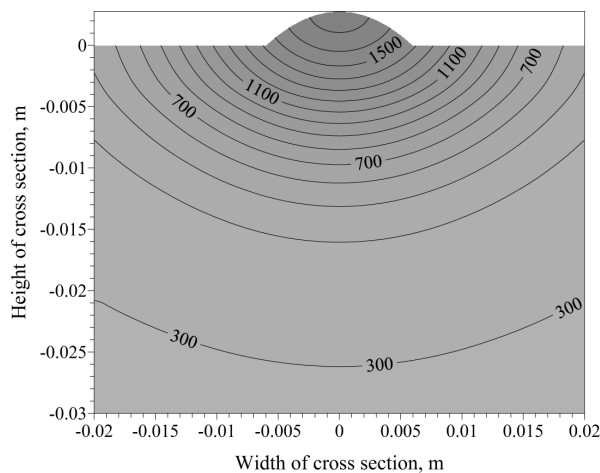

Fig. 5. Temperature field 4 s after the passage of electrode

Figure 6 in turn presents maximum temperatures in cross-section. Temperature distribution on the surface of surfaced steel cast after 25 s of surfacing (10 s after passage above middle cross-section – $x = 0.1$ m) is presented in Figure 7.

The maximum temperature field in cross section allows one to determine the heat affected zone. Figure 8 presents heat affected zones determined by the initial $A_1 = 993$ K and final $A_3 = 1108$ K temperature of austenitic transformation as well as fusion line 1766 K. Fusion line (solidification temperature of steel) in this figure corresponds to fusion line obtained in experiment described by Klimpel et al. [10]. The suggested temperature field model enables one to calculate welding thermal cycle in any point of cross section. Thermal cycles at selected points of cross-section (cf. Fig. 8) are presented in Figure 9.
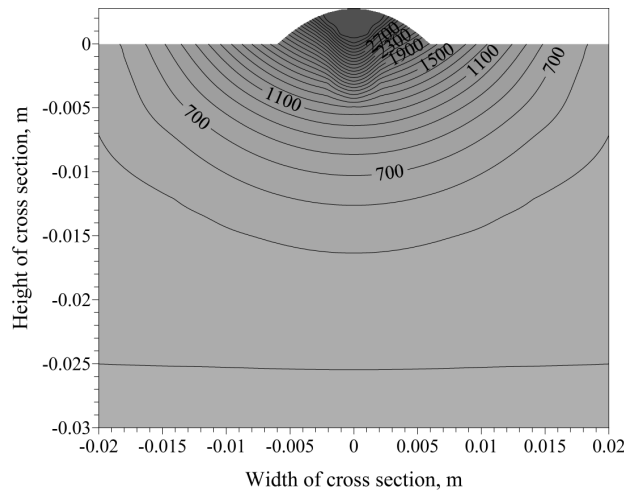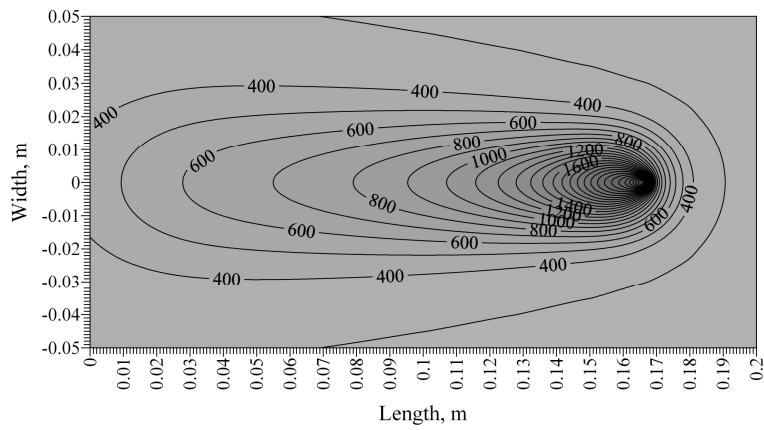
Fig. 6. Maximum temperature field

Fig. 7. Temperature isolines on the surface of arc weld surfaced steel element after 25 s
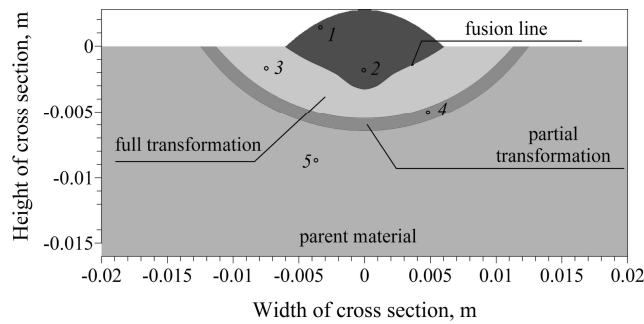of surfacing begin

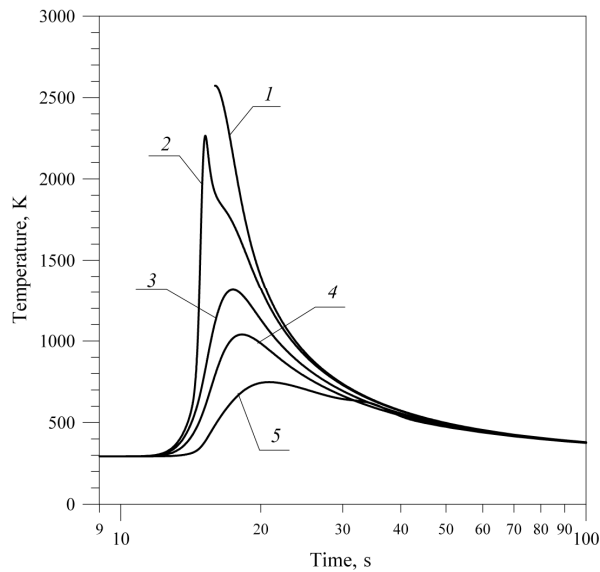Fig. 8. Heat affected zone with selected points

Fig. 9. Thermal cycles at selected points of cross-section

Conclusions

Surfacing is distinguished by application of liquid metal, which spills across the surface and creates an additional heat source. Consideration of this heat source is therefore essential in temperature field solutions. In this work, a temperature field solution of surfacing for a half-infinite body model is presented. The solution is obtained by aggregating temperature accruals caused by applying liquid metal and thermal radiation from a moving electrode. As a comparative criterion of numerical simulations and experimental research results, the shape and measurements of fusion line were assumed. The accuracy of the solution was confirmed by comparison of a calculated fusion line with that obtained experimentally by other authors with the same technological parameters of the process.

The presented model enables the determination of heat affected zone (HAZ), including partial and full transformations and fusion zones, as well as analysis of thermal cycles at any point of the steel cast. The results of numerical simulations indicate a significant influence the heat of weld has on temperature distribution in fusion and full transformation zones.

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