In the work the bimodal heat source model in the description of the temperature field is presented. The electric arc was treated physically as one heat source, whose heat was divided: part of the heat is transferred by the direct impact of the electric arc, but another part of the heat is transferred to the weld by the melted material of the electrode. Computations of the temperature field during SAW surfacing of S355 steel element are carried out. The macrographic and metallographic analysis of the weld confirmed the depth and shapes of the fusion line and HAZ defined by the numerical simulation.

Key words: SAW, HAZ, modeling, temperature, microstructure

INTRODUCTION

In the modelling of the temperature field of welding processes a single-distributed heat source model is generally assumed, reflecting the direct impact of the electric arc on the surfaced object. This approach is found in the description of the temperature field during SAW surfacing using analytical and numerical methods [1-4]. The shape of the fusion lines during surfacing by welding often exhibit shape irregularity that is difficult to restore by means of the description of the temperature field obtained by using the single-distributed heat source model.

MODEL OF TEMPERATURE FIELD

The part of the heat generated by the electric arc is consumed to heat and melt the electrode or the additional material, and then transferred by the cooling weld material to the surfaced object. This gives a justification for the division of the heat generated by an electric arc. The proposed model assumes physically one heat source – an electric arc, and the heat transfer to the surfaced object is divided into the heat transferred directly through the electric arc and through molten material in the form of drops, that under the influence of electromagnetic forces are detached and transferred to the forming weld. The proposed solution of the temperature field is summing temperature fields caused by the heat of direct impact of an electric arc and by the heat of the weld reinforcement (consumed to melt the electrode).

The shape of the weld face is determined mainly by the forces of surface tension. On the basis of experimental research Hrabe and others [5] have proposed a parabolic shape of the face. Lower limit of the imposed metal is defined by the surface shape of surfaced material. In the solution the parabolic model was adopted. Then the geometry of the weld is presented in Figure 1, where $h_w$ is the height of the weld (weld reinforcement – the part of the weld above the surface of the surfaced material), $d_p$ is the depth of material thickness loss (e.g. depth of wear zone), and $\Delta l$ results from considering the volume of material supplied from the electrode.

![Figure 1 Geometry of the weld](image_url)
Analytical description of the temperature field caused by the direct impact of the electric arc with Gaussian heat distribution (Figure 2) is shown in [6], whereas considering the heat stored in the liquid metal imposed on the surface is presented in [7].

For accepted scheme of the single-pass surfacing (Figure 3), where: \( \xi = x - vt - x_0 \) and \( x_0 \) is the coordinate of the start of the weld, the temperature field (1) is defined as follows:

- for time \( t > t_\ast \), where \( t_\ast \) is the total time of making of the weld:

\[
T(x, y, z, z_0, t) - T_0 = A_{c_\ast} \int_0^{t_\ast} \left[ H_\ast \left( t' \right) F_\ast \left( y, z \right) - F_\ast \left( y, z \right) \right] dt' + A_0 \int_0^{t_\ast} F_\ast \left( t' \right) dt'
\]

- for time \( t > t_\ast \):

\[
T(x, y, z, z_0, t) - T_0 = A_{c_\ast} \int_0^{t_\ast} \left[ H_\ast \left( t' \right) G_\ast \left( y, z \right) + G_\ast \left( y, z \right) - G_\ast \left( y, z \right) \right] + A_0 \int_0^{t_\ast} F_\ast \left( t' \right) dt'
\]

where

\[
t_\ast = \frac{1}{v}
\]

\[
A_{h} = \frac{3\dot{q}}{16C_p\rho a
\]

\[
A_{c} = \frac{3\dot{q}}{16C_p\rho a x_0}
\]

Functions \( G_1 \)–\( G_4 \) and \( F_1 \)–\( F_4 \) are solutions of integrals using Gauss-Legendre quadrature [7].

Figures 2 and 3

Figure 2 Gaussian distribution of heat source

Figure 3 Surfacing scheme

\[
A_{c} = \frac{\dot{q}}{8c_\rho \sqrt{\pi a}}
\]

\[
F_\ast \left( t' \right) = \frac{1}{t^{*} + t_0} \exp \left( -\frac{\xi^2}{4a(t^{*} + t_0)^{\frac{3}{2}}} \right)
\]

\[
\left\{ \left( \frac{z^2 + 4a(t^{*})^2}{z_0^2} \right)^{1.5} \left( \frac{\text{erf} \left( \frac{z + z_0}{2(4at^{*})^{1.5}} \right)}{4a(t^{*})^{0.5}} \right) \right\} + \Phi(z) \left( \left( \frac{z + z_0}{2(4at^{*})^{1.5}} \right) \right)^{1.5} - \Phi(z) \left( \left( \frac{z + z_0}{2(4at^{*})^{1.5}} \right) \right)^{1.5} + \Phi(z) \left( \left( \frac{z + z_0}{2(4at^{*})^{1.5}} \right) \right)^{1.5}
\]

\[
H_\ast \left( t' \right) = \frac{1}{\sqrt{\pi t^{*}}} \left( \text{erf} \left( \frac{\Delta l - 2(\xi + vt')}{4\sqrt{at^{*}}} \right) + \text{erf} \left( \frac{\Delta l + 2(\xi + vt')}{4\sqrt{at^{*}}} \right) \right)
\]

\[
H_\ast \left( t' \right) = \frac{1}{\sqrt{\pi t^{*}}} \left( \text{erf} \left( \frac{\Delta l - 2(x - vt - x_0)}{4\sqrt{at^{*}}} \right) + \text{erf} \left( \frac{\Delta l + 2(x - vt - x_0)}{4\sqrt{at^{*}}} \right) \right)
\]

\( a \) - thermal diffusivity / m² s⁻¹, \( C_p \) - specific heat / J kg⁻¹ K⁻¹, \( \rho \) - density / kg m⁻³, \( x_0 \) / m and \( l / m \) are the coordinates of the start and length of the weld respectively. Quantity \( t_\ast / s \) characterizes surface heat source distribution whereas \( r_0^2 = 4at_\ast \) [8] (compare Figure 2). Functions \( G_1 \)–\( G_4 \) and \( F_1 \)–\( F_4 \) are solutions of integrals using Gauss-Legendre quadrature [7].
The total amount of the heat $q_t$ contained in the material of melted electrode is presented by formula [9]:

$$q_t = \Delta q_{\text{solid}} + \Delta q_f + \Delta q_{\text{liquid}}$$  \hspace{1cm} (13)

where $\Delta q_{\text{solid}}$ – the heat required to heat the electrode from the initial temperature to the melting point, $\Delta q_f$ – the heat used to melt the electrode (heat of fusion), $\Delta q_{\text{liquid}}$ – the heat used to heat melted material to the temperature, where a drop of metal falls onto the surface of the surfaced object.

The initial value of the outputted from the welding head electrode temperature is determined on the 100 °C. Accordingly:

$$\dot{q}_t = \dot{m} \left( c (T_e - T_s) + L \right)$$  \hspace{1cm} (14)

where $L$ is the heat of solidification /J kg$^{-1}$,

$$\dot{m} = \rho_e \frac{m}{4} v_e$$  \hspace{1cm} (15)

where: $d$ is the diameter of the electrode, $\rho_e$ is the density of the electrode material and $v_e$ is wire feed speed.

EXAMPLE OF CALCULATION

Calculations of the changeable in time temperature field for a square steel element with the side length 0,2 m and thickness of the plate 0,03 m made from steels S355J2G3 have been conducted. Thermal properties of welded subject material and electrode have been determined by $a = 8 \times 10^{-6}$ m$^2$s$^{-1}$, $C_p = 670$ J kg$^{-1}$ K$^{-1}$, $\rho = 7800$ kg m$^{-3}$ and $L = 268$ kJ kg$^{-1}$.

Numerical simulation has been conducted for the welding heat source of power 3 500 W with Gaussian power density distribution determined by $t_0 = 0,13$ s and $z_0 = 0,008$ m.

The source power corresponds to welding parameters ($U = 30$ V, $I = 400$ A, $\eta = 0,95$) used in the welding experiment. Likewise in the experiment calculations there were assumed welding velocity $v = 0,007$ m s$^{-1}$, electrode wire diameter $d = 3,5$ mm, wire feed speed $v_e = 0,031$ m s$^{-1}$ and bead dimensions $h_w = 2,5$ mm and $w_w = 22$ mm ($d_e = 0$). The initial value of temperature of electrode $T_e = 100$ °C (a temperature of contact tip with the welding head). Computations have been made for middle cross-section of the surfaced element.

In Figure 4 maximum temperature distribution in cross section has been presented. The calculated isotherm 1 493 °C determines the fusion line and isothersms $A_3$ and $A_1$ determine the partial and full austenitization zones (Figure 5). The temperatures $A_3 = 920$ °C and $A_1$...
The macrographic inspections of the weld confirm the depth and regular shapes of the heat affected zone defined by the numerical simulation. The metallographic analysis shows the material structure characteristic for the identified zones (dendritic structure in the reinforcement of the weld and the fusion zone, fine grain structure in fully austenitic transformation). The direction for further research is to analyze the correlation between the parameters of the heat source model and technological parameters of the process and their impact on the temperature distribution (dimensions and shapes of the fusion lines and also the heat affected zones) as well as the kinetics of phase transformation.

REFERENCES


Note: The responsible translator for English language is Izabela Misch, Częstochowa, Poland