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Modelling of Strains During SAW Surfacing Taking into Heat of the Weld in Temperature Field Description and Phase Transformations

J Winczek 1, K Makles 1, M. Guewa 1, R. Gnatowska 1*, M. Hatala 2

1 Faculty of Mechanical Engineering and Computer Science, Czestochowa University of Technology, 42-201 Czestochowa, Poland
2 Faculty of Manufacturing Technologies, Technical University of Kosice with a seat in Prešov, 080 01 Prešov, Slovakia

*Email: rgnatowska@gmail.com

Abstract. In the paper, the model of the thermal and structural strain calculation in a steel element during single-pass SAW surfacing is presented. The temperature field is described analytically assuming a bimodal volumetric model of heat source and a semi-infinite body model of the surfaced (rebuilt) workpiece. The electric arc is treated physically as one heat source. Part of the heat is transferred by the direct impact of the electric arc, while another part of the heat is transferred to the weld by the melted material of the electrode. Kinetics of phase transformations during heating is limited by temperature values at the beginning and at the end of austenitic transformation, while the progress of phase transformations during cooling is determined on the basis of TTT-welding diagram and JMA-K law for diffusive transformations, and K-M law for martensitic transformation. Total strains equal to the sum of thermal and structural strains induced by phase transformations in welding cycle.

1. Introduction
Modeling of thermomechanical states in the surfacing or rebuilding by welding requires the determination of temperature field. Then it is necessary to calculate the shares of structural elements and taking into account their changes that occur as a result of phase transformations. Finally, it enables the determination of thermal and structural strains.

2. The model of temperature field
Modeling the temperature field in many technological processes requires the movement heat source taking into account. Such an approach is found in descriptions of temperature fields in welding processes [1-8], as well as in the machining processes [9], coating formation [10], laser heat treatment [11] and hybrid laser-waterjet micro-machining [12]. In modelling of temperature field during welding dominate two approaches: analytical [3,6,13 - 15] and numerical [5,8, 13-18], looking for a solution for particular welding methods and types of joints. In the analytical description of the temperature field, the bimodal heat source model has been used [19]. This 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 detached and transferred to the forming weld. Then the temperature field is represented by formula:

$$T(x,y,z,t) - T_0 = T_w(x,y,z,t) + T_e(x,y,z,t)$$  \hspace{1cm} (1)
where: \( T_d(x,y,z,t) \) and \( T_u(x,y,z,t) \) are temperature fields caused respectively by the heat of direct impact of an electric arc and by the heat of the weld reinforcement (consumed to melt the electrode). A detailed solution of this temperature field is presented in [20].

3. Description of phase transformation kinetics

Kinetics of phase transformations during heating is limited by temperature values at the beginning \( (A_i) \) and at the end \( (A_f) \) of austenitic transformation. The amount of austenite \( \varphi_i \) created during heating of ferrite-pearlitic steel is defined according to the Johnson-Mehl-Avrami's and Kolomogorov's (JMAK) rule [21]:

\[
\varphi_i(T) = \sum_j \varphi_j^0 \left(1 - \exp\left(-b_j \left(T - T_j^0\right)^m\right)\right), \quad n_j = \frac{\ln(\ln(0.99))}{\ln(A_f / A_i)}, \quad b_j = \frac{0.01}{A_i}
\]  

(2)

where \( \varphi_j^0 \) constitutes initial share of ferrite \( (j=F) \), pearlite \( (j=P) \) and bainite \( (j=B) \), while constants \( b_j \) and \( n_j \) are determined using conditions of the beginning and the end of transformation.

During cooling is estimated using additivity rule by volume fraction \( \varphi_i \) of created phase what can be expressed [22]:

\[
\varphi_i = \varphi_i \varphi_i^\text{ax} \left(1 - \exp\left(-b_i \left(T - T_i^0\right)^m\right)\right) + \varphi_i^0
\]  

\[
n_i = \frac{\ln\left(\ln\left(1 - \varphi_i^f\right) / \ln\left(1 - \varphi_i^f\right)\right)}{\ln\left(T_i^0 \left(1 - \varphi_i^f\right)^m / T_i^0 \left(1 - \varphi_i^f\right)^m\right)}, \quad b_i = \frac{n_i \left(1 - \varphi_i^f\right)}{T_i^0}, \quad \varphi_i^f = 0.01, \quad \varphi_i^\text{ax} = 0.99
\]

(3) \hspace{1cm} (4)

where: \( \varphi_i^0 \) is volume participation of \( j \)-th structural component, which has not been converted during the austenitization, \( T_i^0 = T_i^0(v_{i\alpha}) \) and \( T_i^0 = T_i^0(v_{i\alpha}) \) are respectively initial and final temperature of phase transformation of this component.

The fraction of martensite formed below the temperature \( M_i \) is calculated using the Koistinen-Marburger formula [23]:

\[
\varphi_M(T) = \varphi_M \varphi_M^\text{ax} \left(1 - \exp\left[-\mu(M_i - T)\right]\right) , \quad \mu = \ln(\varphi_M^\text{ax}) / (M_i - M_f)
\]

(5)

where \( \varphi_M \) denotes volumetric fraction of martensite, \( M_i \) and \( M_f \) denote initial and final temperature of martensite transformation respectively, \( T \) the current temperature of process and \( \varphi_M^\text{ax} = 0.1 \).

4. Thermal and structural strains calculation

Total strain during single-pass surfacing represents the sum of thermal and structural strains during heating \( (\varepsilon^H) \) and cooling \( (\varepsilon^C) \):

\[
\varepsilon(x,y,z,t) = \varepsilon^H + \varepsilon^C
\]

(6)

Then strains during heating is equal to:

\[
\varepsilon^H = \sum_{i=A,F,P,B} \left( \alpha_i \varphi_i(T - T_0)H(T - T_i) + \alpha_i \varphi_i(T - T_0)H(T - T_i)\right) + \gamma_i \varphi_i(T - T_i) + \varphi_i\gamma_i \sigma_i
\]

(7)

where: \( \gamma_i \) - structural strain of \( i \)-th structure in austenite, \( T_0 \) - initial temperature, \( \alpha_i \) - linear thermal expansion coefficient of \( i \)-th structure, and \( H(x) \) is the function defined as follows:

\[
H(x) = \begin{cases} 
1 & \text{for } x > 0 \\
0.5 & \text{for } x = 0 \\
0 & \text{for } x < 0 
\end{cases}
\]

(8)

During cooling, the strain can be described by the relation:
\[
\varepsilon^C = \alpha_s (T - T_{SOL})H(T_0 - T_s) + \alpha_f (T_T - T_{SOL})H(T_0 - T) + \sum_{i=A,P,B,M} \alpha_i (T - T_s)H(T_0 - T) + \sum_{i=A,P,B,M} \gamma_i
\]

where \( T_{SOL} \) denotes solidus temperature, \( T_s \) – initial temperature of phase transformation, \( T_T \) - initial temperature of austenite transformation in \( i \)-th structure, \( \gamma_i \) – structural strain of austenite in \( i \)-th structure. In addition, due to the limit on solid state of material:

\[
\varepsilon(x,y,z,t) = 0 \quad \text{for} \quad T > T_{SOL}
\]

5. Example of thermal and structural strains during SAW surfacing

Calculations of the temporary 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 \( a = 8 \cdot 10^{-6} \text{ m}^2/\text{s} \), \( C_p = 670 \text{ J/kg K} \), \( \rho = 7800 \text{ kg/m}^3 \) and \( L = 268 \text{ kJ/kg} \). Numerical simulation has been conducted for the welding heat source of power 3500 W, which corresponds to welding parameters \( (U = 30 \text{ V}, I = 400 \text{ A}, \eta = 0.95) \). The initial value of the temperature of electrode \( T_e = 100 \degree \text{C} \) (a temperature of contact tip with the welding head). Computations have been made for a middle cross-section of the surfaced element.

![Figure 1. Maximum temperature field](image)

![Figure 2. Calculated heat affected zones](image)

![Figure 3. TTT-welding diagram for S355 steel](image)

In Figure 1 maximum temperature distribution in cross section has been presented. The calculated isotherm 1493 \degree \text{C} determines the fusion line and isotherms \( A_3 \) and \( A_1 \) determine the partial and full austenitization zones (Fig. 2). In Figure 2, the selected cross section points were marked, for which a stress analysis was performed. The temperatures \( A_3 = 920 \degree \text{C} \) and \( A_1 = 748 \degree \text{C} \) have been calculated taking into account the effect of heating rate on these temperatures [24].

The phase transformations kinetics during heating is limited by the temperatures \( A_1 \) of the beginning and \( A_3 \) the end of the austenite transformation, while the progress of phase transformations during cooling was determined on the basis of TTT-welding diagram for S355 steel shown in Figure 3 [25].

| Phase       | \( \alpha \) \([1/\degree \text{C}]\) | \( \gamma \) |
|-------------|--------------------------------|-------------|
| Austenite   | \( 2.178 \cdot 10^{-5} \) \( \gamma_{E,P,A} \) | \( 1.986 \cdot 10^{-5} \) |
| Ferrite     | \( 1.534 \cdot 10^{-5} \) \( \gamma_{B,A} \) | \( 1.440 \cdot 10^{-5} \) |
| Pearlite    | \( 1.534 \cdot 10^{-5} \) \( \gamma_{A,P,B} \) | \( 3.055 \cdot 10^{-5} \) |
| Bainite     | \( 1.171 \cdot 10^{-5} \) \( \gamma_{A,B} \) | \( 4.0 \cdot 10^{-5} \) |
| Martensite  | \( 1.36 \cdot 10^{-5} \) | |
In strain calculations, there were assumed linear expansion coefficients of particular structural elements and structural stresses (Tab. 1) determined on the basis of the author's own dilatometric research [26]. Dilatometric graphs for selected cross-sectional points (see Fig. 2) were shown in Figures 4 – 7. These diagrams correspond to Figures 8 - 11 that show the history of temperature and strain changes during surfacing. In point 1 (Figs. 4, 8), after solidification of the material, a graph begins at 1493 °C with a rectilinear section reflecting the shrinkage of the material. Cooling transformations are causing faults in the graph, then a graph again assumes the shape of a straight line. In point 2 (Figs. 5, 9), the complete austenitization occurred during heating, whereas during cooling the austenite was converted into the hardening structures, which is visible in the form of characteristic faults on the graph. In point 3 (Figs. 6, 10) occurred the incomplete conversion of austenitic. In point 4 (Figs. 7, 11) did not have a phase transition and the graph is straight-line.

Figure 4. Dilatometric diagram for point 1.  
Figure 5. Dilatometric diagram for point 2.  
Figure 6. Dilatometric diagram for point 3.  
Figure 7. Dilatometric diagram for point 4.
6. Conclusion
The presented analytical approaches allow for the computation of the temperature field, the volume participation of the structural phases and thermal and structural strains in single-pass SAW surfacing or rebuilding steel elements. Consequently, it allows for: the determination of HAZ, welding thermal cycles, the change of volume phase participations of the structural components and the strains caused by the temperature field and the phase transformations, the effect of the temperature field and the structural composition on the formation and development of strains during the deposition process at any point of SAW surfaced object. The paper presents the results of calculations of thermal and structural strains during the welding process using the SAW method. Calculated welding heat cycles and volume shares of particular structural components allowed for the determination of the size of the thermal and structural strains. The obtained results provide the basis for calculating the strain states.

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