Prediction of structure and mechanical properties of welded joints using analytical methods

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Abstract

The paper presents analytical methods of the prediction of mechanical properties of welded joints made of S355 steel. Formulas determining so called characteristic temperatures and times for corresponding phase transformations are used in order to build computational CCT diagrams. These empirical relationships are presented in correlation with corresponding cooling rates \( v_{8/5}(t_{8/5}) \). Additionally, volume fractions of each phase are determined as a function of cooling rate using analytical models. Mechanical properties of welded joints made of S355 steel are predicted on the basis of obtained phase fractions. Dilatometric research on S355 steel is performed in order to verify obtained analytical results and to evaluate the usefulness of created diagrams of austenite transformation.

Keywords: analytical methods; phase transformations; mechanical properties; heat affected zone

1. Introduction

Material during welding changes its thermophysical and mechanical properties due to changing temperature field in a wide range. The most various material properties occur in the heat affected zone (HAZ). In this area a large variety of structures occurs conditioned by thermal cycles as a result of phase transformations in solid state. Many relationships can be found in the literature concerning the prediction of structure and mechanical properties in HAZ, determined by chemical compositions [1–7]. These relationships are used to create simplified CCT diagrams of austenite transformation.
diagrams and to estimate mechanical properties in HAZ of welded joints. Results obtained by analytical methods are often used in the initial analysis of material properties, preceding experimental studies and during the development of mathematical models. Most often CCT diagrams are extended by diagrams of changes of hardness (HV), impact strength (KCU), yield strength (Re), tensile strength (Rm), contraction (Z) and elongation (A5) in the function of time $t_{85}$ [1, 8]. Mechanical properties in HAZ are determined by microstructure occurring in this area as well as stress and strain states.

This paper presents a possibility of using analytical methods to predict mechanical properties in welded elements. Analytical models used in this paper concern the prediction of mechanical properties of welded steel, obtained on the basis of chemical compositions and calculated phase volume fractions of steel. Phase fractions are determined experimentally in this work, on which mechanical properties such as: hardness (HV), impact strength (KCU), yield strength (Re), tensile strength (Rm), contraction (Z) and elongation (A5) in the function of time $t_{85}$ are designated. Results of the prediction of mechanical properties of welded steel using analytical methods are presented for electric arc butt-welding process.

2. Experimental CCT diagram for S355 steel

Dilatometric research is performed using DIL805 Bahr Thermoanalyse GmbH dilatometer for S355 steel with chemical composition shown in Table 1. Austenitization temperature $T_A = 1200$ °C and heating rate $v_H = 100 \text{ K.s}^{-1}$ are assumed in dilatometric research as well as different cooling rates simulating thermal cycles during welding. Dilatometric and microstructural analysis is supported by microhardness measurement, applied to evaluate dilatometric samples. Fig. 1 presents CCT diagram of S355 steel obtained in dilatometric research for different cooling rates $v_{85}$, where $v_{85} = (800 - 500)/t_{85}$ and $t_{85}$ is a cooling time in the range of 800–500 °C. Fig. 1 shows also final volumetric fractions of phases (final structure composition of analyzed steel) for specified cooling rates [5].

Table 1. Chemical composition of S355 steel in %.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355</td>
<td>0.19</td>
<td>1.05</td>
<td>0.20</td>
<td>0.028</td>
<td>0.02</td>
<td>0.006</td>
<td>0.08</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Fig. 1. Experimental CCT diagram and phase fractions of S355 steel [5].
Volumetric fractions of each structure, like: ferrite (F), pearlite (P), bainite (B) and martensite (M) corresponding to CCT diagram are used to determine the mechanical properties of the weld and heat affected zone of welded joint.

3. Analytical models to predict mechanical properties in welded joints

Mechanical properties of HAZ can be determined from the structural composition and mechanical properties of each structure. If the phase composition in the heat affected zone is known, more specifically contribution of each structure (ferrite-pearlite, martensite and bainite) and properties of structural components $W_i$, there is a possibility to approximately predict properties of the entire zone [8]:

$$ W = \sum_{i=M,F,P,B} W_i \eta_i $$  

(1)

where $W$ can be hardness, yield strength, tensile strength, impact strength, elongation and contraction.

Many dependencies are discussed in the literature [9, 10], which can determine mechanical properties such as: $Re$, $Rm$, $A_5$, $Z$, $KCU$ and $HV$. Property of each phase: ferrite-pearlite, martensite and bainite are defined on the base of chemical composition, whereas contributions of each phase are defined on the base of experiment or through the use of analytical methods [8].

Yield strength and tensile strength of each phase: ferrite-pearlite, martensite and bainite can be determined with a high probability by Kasatin and Seyffart equations [9]. These equations are determined by steel chemical composition:

- **Yield strength**
  
  $$ Re_f = 602 + 2150C + 400Mo $$  
  $$ Re_p = 500 + 460C - 120C^2 + 150V + 360Mo $$  
  $$ Re_m = 187 + 92C + 47Mn + 90V $$  

(2)

- **Tensile strength**
  
  $$ Rm_f = 798 + 3215C $$  
  $$ Rm_p = 590 + 960C + 39.7Mn + 200V $$  
  $$ Rm_m = 297 + 1360C + 60Mn + 140V $$  

(3)

Hardness, mapping the structural heterogeneity of HAZ, is one of the basic volume which characterizes welded joint. Hardness of HAZ is a function of phase composition $\eta_i$ and hardness of each structure constituent $HV_i$ ($i$ means each phase such as: ferrite-pearlite, martensite and bainite). Hardness $HV_i$ of individual structural components can be defined by [9] as a function of chemical composition and velocity $v_{8/5}$ ($v_{8/5} = (800 - 500)/1005$):

$$ HV_f = -323 + 185C + 330Si + 153Mn + 65Ni + 144Cr + 191Mo + (89 + 53C - 55Si + $$
$$ - 22Mn - 10Ni - 20Cr - 33Mo) \log v_{8/5} $$

$$ HV_p = 42 + 223C + 53Si + 30Mn + 12.6Ni + 7Cr + 19Mo + (10 - 19Si + 4Ni + 8Cr + $$
$$ + 130V) \log v_{8/5} $$

$$ HV_m = 127 + 959C + 27Si + 11Mn + 8Ni + 16Cr + 21 \log v_{8/5} $$

(4)

Impact strength ($KCU$), elongation ($A_i$) and contraction ($Z_i$) for structure components can be defined by [10] as a function of steel chemical composition and time $t$, where $t$ is the cooling time between temperatures 800 °C and 500 °C:
• Impact strength

\[
KCU'_{\mu} = 1.06 - 2.8C + 1.3C^2 - 0.081Mn + 0.054\ln t \\
KCU'_{\nu} = 1.3 - 1.6C - 0.08Mn \\
KCU'_{\nu\nu} = 1.47 - 1.8C + 0.80C^2 - 0.076Mn - 0.045\ln t
\]  

(5)

• Elongation

\[
A_{\mu} = 12.267C^3 - 1.5Mn + 0.76\ln t \\
A_{\nu} = 21.3 - 35.6C - 4.0Mn - 5.0V + 1.84\ln t \\
A_{\nu\nu} = 36.5 - 127C + 153C^2 - 1.16Mn + 8.0V + 0.66\ln t
\]  

(6)

• Contraction

\[
Z_{\mu} = 48.5 - 158C + 116C^2 - 0.98\ln t \\
Z_{\nu} = 53.3 - 132C + 103C^2 - 5.1Mn - 10V + 3.4\ln t \\
Z_{\nu\nu} = 65.4 - 88C - 82C^2 - 6.7Mn + 18V + 0.6\ln t
\]  

(7)

4. Exemplary prediction of mechanical properties in HAZ using analytical methods

An example of the prediction of mechanical properties in HAZ is presented in this paper. The electric arc butt-welding of S355 steel sheets with dimensions 150×30×3 mm is considered. Temperature field in welded joints is determined using Abaqus FEA engineering software. The analysis of thermal phenomena is made on the basis of the numerical solution of energy conservation equation together with Fourier law [11] using finite element method (FEM). The temperature field expressed in the criterion of weighted residuals method is described by the following equation:

\[
\int \rho \frac{\partial U}{\partial t} dV + \int \rho \frac{\partial \theta}{\partial t} dV = \int \lambda \frac{\partial T}{\partial x_{i}} dV = \int q_{i} dV + \int \theta dS
\]  

(8)

where \( \lambda \) is a thermal conductivity (W.m⁻¹K⁻¹), \( U \) is the internal energy (J.kg⁻¹), \( q_{i} \) is the capacity of the laser beam power (W.m⁻³), \( T = T(x_{a},t) \) is a temperature (K), \( q_{i} \) is a density of heat flux (W.m⁻²), \( \theta \) is a partial differential of \( T \).

The above equation is completed by initial and boundary condition of Dirichlet, Neumann and Newton type with heat loss due to convection and radiation. Movable welding source is implemented in Abaqus FEA [11] using additional numerical DFLUX subroutine. “Double elliptical” volumetric heat source model presented by Goldak [12] is used in calculations. In the analysis of temperature field the power of electric arc is set to \( Q = 2200 \) W and welding speed \( v = 9 \) mm.s⁻¹:

\[
q_{f}(x,y,z) = \frac{6\sqrt{3}f_{r}Q}{abc\pi\sqrt{\pi}} \exp(-3\frac{x^2}{a^2})\exp(-3\frac{y^2}{c^2})\exp(-3\frac{z^2}{b^2})
\]  

(11)

\[
q_{r}(x,y,z) = \frac{6\sqrt{3}f_{r}Q}{abc\pi\sqrt{\pi}} \exp(-3\frac{x^2}{a^2})\exp(-3\frac{y^2}{c^2})\exp(-3\frac{z^2}{b^2})
\]  

(12)

\[
q(x,y,z) = q_{f}(x,y,z) + q_{r}(x,y,z)
\]  

(13)

where \( a, b, c_{f}, c_{r} \) are dimensions of semi-ellipsoid axes, \( f_{r} \) and \( f_{f} \) are values representing energy distribution in the front and in the rear parts of the heat source, satisfying the condition \( f_{r} + f_{f} = 2 \), \( Q \) is a power of electric arc.
Numerical calculations of the temperature field are performed as 3D task. Analysis of mechanical properties is performed on the basis of determined temperature distribution (Fig. 2) [13]. In Fig. 2 cross section of considered welded joint is presented. This figure also presents temperature distribution in the central layer, at different distances from the axis of the source, where characteristic \( t_{8/5} \) times are pointed out. Results of the analysis for chosen points at various distances from the weld line are presented in the cross section of the weld (points 1, 2, 3 and 4). Points 1 and 2 that are marked in Fig. 2 belong to the weld, while points 3 and 4 belong to the heat affected zone.

Prediction of mechanical properties in the weld and HAZ are performed using relationships (2)–(7) and experimentally defined volume fractions. Distributions of mechanical properties as a function of time \( t_{8/5} \) determined by analytical methods in the cross-section of welded joint as a function of the distance from the weld line (points 1, 2, 3 and 4) are presented in Figs. 3–5. In comparison, the mechanical properties obtained for the time \( t_{8/5} = 8 \) s (point 2), according to [1] are: \( R_e = 720 \) MPa, \( R_m = 1000 \) MPa, \( Z = 30 \% \), \( A = 13 \% \), \( HV = 560 \), \( KCU = 80 \) J.cm\(^{-2} \).

![Fig. 2. Temperature distribution in considered joint [13].](image1)

![Fig. 3. Yield strength (Re), tensile strength (Rm) in welded joint determined for characteristic points.](image2)

![Fig. 4. Contraction (Z) and elongation (A) in welded joint determined for characteristic points.](image3)
5. Conclusions

The usefulness of analytical methods used to predict mechanical properties in HAZ is assessed in this work. Experimentally obtained phase fractions of ferrite, pearlite, bainite and martensite are used to determine mechanical properties of welded joint as well as mechanical properties of different structures determined using analytical methods. Determined mechanical properties of the material in the weld and HAZ are the result of used welding technology, temperature distribution in the material and phase transformations in solid state.

Mechanical properties obtained using analytical methods can be applied for the preliminary analysis of material properties intended for different welded constructions. They can also be used as input data in numerical analysis of stresses and deformations in welded elements, substituting expensive experimental research in this field.

References