Three-Dimensional Simulation of Underwater Welding and Investigation of Effective Parameters

The three-dimensional finite difference method was used to obtain temperature profiles, thermal history curves, and cooling times for single-pass underwater wet weldments

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ABSTRACT

The results of three-dimensional numerical simulation of wet underwater welding in thin steel plates were studied. Temperature profile, thermal history curves as well as cooling time for single-pass underwater wet weldments were obtained by solving the appropriate heat transfer equations using the three-dimensional finite difference method. The model was validated using experimental data for the air welding process. The effect of the parameters such as material, surrounding fluid, convective heat coefficient (h_c), arc heat model, and the method of heat losses from the plate were investigated through modeling and analyzing ten different case studies. The obtained results indicate that the type of surrounding fluid has a significant role in the temperature variations during welding and consequently cooling time is much lower in underwater welding compared with welding in air. The effect of material type could not be distinguished, obviously because of the rapid cooling in wet welding. The analysis using the Tsai model for h_c in comparison with constant values indicates the Tsai model can predict h_c successfully, when its value is 1000–6000 W/m²K. The method of arc heat estimation is important when the temperature distribution in short vertical distances from the weld interface is considered and, at other positions, there is no difference between the two used arc heat estimations. The results show that the convective heat transfer is more effective than radiation in temperature calculations; therefore the radiation can be neglected.

Introduction

Ship salvage, harbor clearance, wreck removal, underwater pipelines, and conveying equipment repair oftentimes require extensive underwater cutting and welding. Beginning in the mid-1930s, with the substitution of welding for lesser quality mechanical methods of joining, the overall cost and time spent on the job could be reduced considerably (Refs. 1–3).

Underwater welding processes are classified as dry or wet based on their exposure to the ambient environment. Processes that are physically protected from the surrounding water are classified as dry, whereas in wet welding, the weld is directly exposed to the underwater environment (Ref. 4). Because of its lower costs, faster and more flexible operation, wet underwater welding offers more advantages than dry underwater welding (Refs. 2, 4). The term “underwater welding” as used in this paper refers to the wet welding technique where no mechanical barrier separates the welding arc from the surrounding water.

While shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) are both used for wet welding, SMAW is the most used process in wet applications (Refs. 1, 5, 6). Shielded metal arc welding offers the benefits of low cost and process simplicity, and has a considerable history of offshore application. However, for the joining of materials at depths exceeding 100 m, GTAW is often selected because of the quality of the welds produced (Ref. 5). Underwater SMAW is somewhat similar to SMAW performed in air (Ref. 7). In the SMAW process, heating with an electric arc is established between an electrode and the base plate, while in wet SMAW, the arc is in the water between the electrode and the surface being welded (Refs. 1, 4, 7).

In the case of gas tungsten arc welding, the arc is drawn between a water-cooled nonconsumable tungsten electrode and the plate. An inert gas shield is provided to protect the weld metal from the atmosphere, and filler metal may be added to the weld pool as required. Ignition of the arc is obtained by means of a high-frequency discharge across the root opening, since it is not advisable to strike an arc on the plate with the tungsten electrode. Normally, the inert gas shield used for welding aluminum and steel in countries like Great Britain is argon. Gas metal arc welding (GMAW) is, in effect, an extension of GTAW in which the electrode in this process is a consumable metal wire (Ref. 8).

There are two major drawbacks during underwater welding: 1) rapid cooling of weld metal and heat-affected zone (HAZ) in comparison to welding in air, and 2) susceptibility to hydrogen embrittlement. In fact, the water acts as a large heat sink and draws off the heat of the electrode so that weld defects induced by the accelerated cooling usually appear in the HAZ in underwater welds. Also, since underwater welding induces an arc atmosphere that is high in water vapor content and in disso-

KEYWORDS

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Wet Welding
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Three-Dimensional Modeling
Shielded Metal Arc Welding (SMAW)
Gas Tungsten Arc Welding (GTAW)
WELDING RESEARCH

for single-pass GTA weldments made in air, a very accurate thermal history can be derived. Some years later, FEA was introduced as another numerical method for solving the welding heat transfer problems. In some recent research, FVM has also been used as the numerical scheme. Much research has been conducted about the temperature field of conventional welding in air, but there has been limited research about underwater welding. Here, some underwater examples using each of the numerical methods are reviewed.

Numerical simulation of the temperature distribution during the welding process can be used to improve wet underwater welding (Ref. 2). An important step toward resolving any kind of deformation and stress problem in the welding applications is the determination of the most appropriate resolution of the temperature distribution. Over the years, many different scientific approaches to the solution of this problem were developed. Among them are (Ref. 3)

1. A whole series of analytical models, from the simplest 1-D solutions to complicated 3-D models taking into account the 3-D heat source distribution and heat losses from workpiece surfaces;
2. Finite difference method (FDM);
3. Finite element analysis (FEA);

In the early years, analytical expressions have been used to describe the thermal history of weldments made in air. This approach has been improved by the development of finite difference models that rely on fewer simplifying assumptions and, for single-pass GTA weldments made in air, a very accurate thermal history can be derived. Some years later, FEA was introduced as another numerical method for solving the welding heat transfer problems. In some recent research, FVM has also been used as the numerical scheme. Much research has been conducted about the temperature field of conventional welding in air, but there has been limited research about underwater welding. Here, some underwater examples using each of the numerical methods are reviewed.

In 1984, Opperer and Szekely examined the stationary, axisymmetric GTAW process with a moving boundary by using the finite difference method (Ref. 10). Fukuoka and Fukui (Ref. 11) compared the cooling processes of underwater welding by gas shielded arc welding with conditions involving welding in air using experimental technique and numerical approach and Tsai and Masubuchi's semi-empirical correlation in his model to obtain the weldment temperature time trend during welding process for an underwater case in comparison with air surroundings.

In a number of works, the numerical calculations of the temperature field and the stress distribution in a thick plate welded underwater have been performed at subsequent time steps by means of FEA (Ref. 12). For instance, in 1994, Hamann and Mahrenholtz (Ref. 13) developed a new welding model for the plasma-GMAW underwater welding technique. They solved the temperature problem using FEA and compared their numerical and experimental data to investigate the influence of surface heat transfer on the temperature distribution during wet underwater welding. In 2007, Xiwen et al. (Ref. 14) simulated a three-dimensional temperature field of a plate weldment in underwater welding. They analyzed the influence of several factors that affect the temperature fields of underwater welding using FEA applied by ANSYS software.

The finite volume method is the least used numerical method in underwater welding. Isikilar and Girgin, in 2011 (Ref. 15), developed a numerical model for transient three-dimensional conduction heat transfer in an underwater welding process on a thick rectangular plate. The numerical scheme was based on a FVM model including convection, radiation, and boiling surface thermal boundary conditions.

On the other hand, the FDM numerical solution has some advantages in comparison with FEA, including the following (Refs. 3, 7, 16):

• The FDM is easily understandable physically (the variables are temperature, time, geometry, and material properties; in contrast to some mathematical functions involved in the FEA solution).
• FDM is simple to formulate and requires less computational work to arrive at a solution.
• Unlike FEA, the accuracy of FDM can

Table 1 — Experimental Characteristics of the Validation Case (Ref. 17)

<table>
<thead>
<tr>
<th>Surrounding Medium</th>
<th>Plate Thickness (mm)</th>
<th>Left Plate</th>
<th>Right Plate</th>
<th>Locations of the Thermocouples from Weld Line (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>3</td>
<td>St37</td>
<td>St37</td>
<td>A  3  B  18  C  23</td>
</tr>
</tbody>
</table>
be examined by order of truncation error in the Taylor series expansion. The FDM is easy to apply for solution of engineering problems involving simple geometry. It is always possible to reduce the size of the uniform mesh steps encountered in FDM to account approximately for the curved geometrical parts.

Based on the extensive review made by the authors over the widespread research on welding simulation by FDM, the underwater welding process simulation by this method and the study of the effective parameters are not well known. In the present work, a finite difference model that predicts the time-temperature history of the underwater weldments made on two different types of steel will be developed. The welding process in this work is a GTAW type in which the electrode is nonconsumable and there is no melting heat consideration in the calculation process. This scheme uses the fusion zone boundary condition for the solution of the resulting nonlinear partial differential equation. Heat transfer to the surrounding water is accounted for using the model of Tsai et al., which was described earlier in this section.

Methodology

Thermal Model

The specific form of the energy equation generalized for the three-dimensional modeling, utilizing the stationary coordinate and unsteady heat conduction to analyze the heat transfer, is developed as

\[
\rho c \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + Q
\]

where \( Q \) [W·m\(^{-3}\)] is the volumetric heat generation, \( \kappa_x, \kappa_y, \) and \( \kappa_z \) are the directional heat conduction coefficients, \( \rho \) [kg·m\(^{-3}\)] is the density of conducting material, and \( C \) [J·kg\(^{-1}\)·K\(^{-1}\)] is the constant pressure heat capacity. Here, no heat generation occurs and thermal conductivity is an isotropic property that is the same in all directions.

In the case of welding applications, the initial condition is usually isothermal, i.e., \( T(x,y,z,0) = T_0 = \text{const} \). The overall governing boundary condition is expressed as

\[
\kappa_x \frac{\partial T}{\partial x} + \kappa_y \frac{\partial T}{\partial y} + \kappa_z \frac{\partial T}{\partial z} + q_s + q_c + q_r = 0
\]

where \( N \) is the directional cosine of the boundaries, and \( q_s, q_c, \) and \( q_r \) are the heat transferred due to the arc heat source, and the convective and radiative heat losses from the solid body, respectively.

Table 2 — Welding Parameters (Ref. 17)

<table>
<thead>
<tr>
<th>Welding Voltage (V)</th>
<th>Welding Current (I)</th>
<th>Welding Speed (mm/s)</th>
<th>Arc Efficiency</th>
<th>Shielding Gas (Ar) (L/min)</th>
<th>Heat Input (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.6</td>
<td>101</td>
<td>1.8</td>
<td>50%</td>
<td>10</td>
<td>0.409</td>
</tr>
</tbody>
</table>

Fig. 3 — Temperature history. Comparison between finite difference results and experimental data (Ref. 17) at points with different distances from the weld interface: A — Point A, 3 mm; B — point B, 18 mm; C — point C, 23 mm.
Finite Difference Method

The weld pool in this model is moved incrementally through the coordinate system at the defined weld speed, using the results of each previous step as the initial condition to the next.

Based on the three-point finite differences, the second-order derivative terms of the left side of Equation 1 at arbitrary node with position of i, j, k in x, y, z direction and in time step n, discrete are as follows:

\[
\frac{\partial^2 T}{\partial t^2} = \frac{T_{i,j,k+1} - 2T_{i,j,k} + T_{i,j,k-1}}{\Delta t^2},
\]

\[
\frac{\partial^2 T}{\partial x^2} = \frac{T_{i+1,j,k} - 2T_{i,j,k} + T_{i-1,j,k}}{\Delta x^2},
\]

\[
\frac{\partial^2 T}{\partial z^2} = \frac{T_{i,j,k+1} - 2T_{i,j,k} + T_{i,j,k-1}}{\Delta z^2}.
\] (4)

In this equation, the \(\Delta x\), \(\Delta y\), and \(\Delta z\) are the distances between the consecutive nodes in x, y, z direction. On the other hand, the first-order derivative term of the right side of Equation 1 at arbitrary node and time step n, based on the forward difference formula discrete, is as follows:

\[
\frac{\partial T}{\partial t} = \frac{T_{i,j,k}^{n+1} - T_{i,j,k}^n}{\Delta t}.
\] (5)

where \(\Delta t\) is the time space. By using Equations 4 and 5, the temperature for a typical internal node is obtained as

\[
T_{i,j,k}^{n+1} = \beta T_{i,j,k}^n + \lambda_1 T_{i+1,j,k}^n + \lambda_2 T_{i,j,k+1}^n + \lambda_3 T_{i,j,k-1}^n + \lambda_4 T_{i-1,j,k}^n.
\] (6)

where \(\alpha\) is the thermal diffusivity, defined as

\[
\alpha = \frac{k}{\rho C}.
\] (8)

An explicit finite difference scheme was chosen for the solution to this model, which can be generally defined as

\[
(T)^{n+1} = [A](T)^n + [B].
\] (9)

The coefficient matrix and constant column matrix in the internal domain for the three-dimensional problem are defined as

\[
A = \begin{bmatrix}
\beta & \lambda_1 & 0 & \lambda_2 & 0 & \lambda_3 & 0 \\
\lambda_1 & \beta & 0 & \lambda_2 & 0 & \lambda_3 & 0 \\
0 & \lambda_1 & \beta & 0 & \lambda_2 & 0 & \lambda_3 \\
0 & 0 & \lambda_1 & \beta & 0 & \lambda_2 & 0 \\
0 & 0 & 0 & \lambda_1 & \beta & 0 & \lambda_2 \\
\end{bmatrix},
\]

\[
B = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}.
\] (10)

For the boundary nodes, Equation 3 is discretized using backward or forward difference formula proportional to the position of the node, similar to discretization of the right side of Equation 1.

Model Validation

Computer codes should be carefully validated before being used to predict the welding process in underwater situations. For this purpose, the validity of the current numerical code has been checked and compared against the published data reported by Attarha and Sattari-Far (Ref. 17). They carried out GTAW experiments in the air for joints comprised of 200 × 200 × 3-mm
plates made of ST37 carbon steel thin plate and also developed a 3D finite element simulation for prediction of the temperature distributions and histories that displayed good accordance with their experimental measurements. In the present study, to validate the FDM results, data from one of their experiments was chosen to be simulated by the current code. The experiment specifications are summarized in Table 1. Figure 1 shows the thermocouple locations.

The voltage (V), current (I), and travel speed (υ) of the weld passes in each joint are given in Table 2.

A temperature-dependent combined convection coefficient has been used to model the cooling condition. Table 3 presents the temperature-dependent convection coefficients for the welding process in air.

### Underwater Welding

The welding of two metal plates with an equal size of 50 × 100 × 2 mm in (x,y,z) coordinates was studied at underwater welding conditions. Steels used in shipbuilding must meet the specified minimum yield strength values. They must be resistant to the initiation of brittle fracture and also to fatigue. One effective method for preventing underbead cracking is to attempt to prevent excessive/hard martensite formation. This method involves controlling the carbon equivalent (CE) of the base metal and the electrode. To prevent underbead cracking, a base plate with a

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**Table 3 — Temperature-Dependent Combined Convection Coefficient Model (Ref. 18)**

<table>
<thead>
<tr>
<th>h (W/m²K)</th>
<th>T – T₀(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85</td>
<td>56</td>
</tr>
<tr>
<td>9.079</td>
<td>278</td>
</tr>
<tr>
<td>18.5</td>
<td>556</td>
</tr>
<tr>
<td>52.6</td>
<td>2778</td>
</tr>
</tbody>
</table>

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**Table 4 — Thermo-physical Properties of Mild Steel and AISI Type 304 Stainless Steel Used in the Simulation (Refs. 17, 19)**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1200</th>
<th>1300</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>k (W/mK)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AISI 304</td>
<td>462</td>
<td>496</td>
<td>512</td>
<td>525</td>
<td>540</td>
<td>577</td>
<td>604</td>
<td>676</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>C_p (J/kgK)</td>
<td>7900</td>
<td>7880</td>
<td>7830</td>
<td>7790</td>
<td>7550</td>
<td>7660</td>
<td>7560</td>
<td>7370</td>
<td>7320</td>
<td></td>
</tr>
<tr>
<td>(kg/m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>0</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>k (W/mK)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild Steel</td>
<td>486</td>
<td>486</td>
<td>515</td>
<td>548</td>
<td>586</td>
<td>649</td>
<td>708</td>
<td>777</td>
<td>624</td>
<td>548</td>
<td>548</td>
</tr>
<tr>
<td>C_p (J/kgK)</td>
<td>7700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kg/m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
lower CE can be used or, alternatively, steel base plates with carbon contents of less than 0.1 wt-% can be welded (Ref. 6). The steels for the commercial ships are subdivided into two strength classes: normal strength and higher strength. In this work, two materials have been investigated: 1) AISI Type 304 stainless steel, which is a higher-strength steel, and 2) mild steel. The material properties are presented in Table 4.

In underwater welding, the arc heat source term in Equation 3, as well as the convective and radiation heats, are different from weldments produced in air. In air welding, the heat losses from the molten surface outside the heat input circle are basically due to radiation. Heat losses from the surface, which is at some distance from the arc, are due to natural convection. However, in underwater welding, very fast cooling in the weldment is usually experienced. According to the observation of the high-speed cinematography, heat losses during underwater welding are mainly due to the heat conduction that transports heat from the plate surface into the moving water environment whose motion is created by the rising of the gas bubble column in the arc area. No boiling phenomena are observed anywhere except in the arc bubble zone. Accordingly, the heat loss mechanism is basically dependent on the water flow field, which is a function of gas formed in the arc and its flow rate (Ref. 20). In the case of an underwater weld, the heat loss through the surface of a welded plate becomes significant when the heat transfer coefficient increases by a factor of 100 over that which is experienced in the air (Ref. 7). Unfortunately, heat transfer from the surface of a hot welded plate to the surrounding water is very complex, in which case either the proposed relations are very complicated (Refs. 14, 21) or the convection coefficient is assumed constant (Refs. 22, 23). Most of these relations calculate a local convection coefficient that needs to be averaged using an appropriate averaging equation. However, Tsai et al. have suggested the use of a semiempirical correlation for the average heat transfer coefficient, based on their observation of bubble dynamics in the vicinity of the arc (Refs. 3, 7).

The semi-empirical correlation developed by Tsai and Masubuchi (Ref. 20) is generally used to define the average surface heat transfer coefficient of the underwater weldments as:

$$h = 675(T_s - T_w)^{1/4}$$  \hspace{1cm} (11)

where $T_s$ is the temperature of the plate surface and $T_w$ is the temperature of the surrounding water. To simplify the calculation, the overall heat transmission coefficient can also be chosen as constant value, as reported in the literature for the underwater weld (Refs. 24, 25). For the radiation heat transfer term, the net radiation heat loss rate can be expressed as

$$q_r = \varepsilon \sigma (T_h^4 - T_c^4) A_c$$  \hspace{1cm} (12)

where $T_h$ is the hot body absolute temperature (K), $T_c$ is the cold surroundings absolute temperature (K), and $A_c$ is the area of the object (m$^2$). The epsilon ($\varepsilon$) coefficient is equal to 0.85 for the weathered stainless steel in water (Ref. 26), which is used in the present calculations.

The heat input distribution of the arc has a Gaussian distribution on the top face of the workpiece. The general equation is (Ref. 21)

Table 5 — The Studied Cases and Their Applied Parameters in the Underwater Welding Computational Model

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Arc Heat Input</th>
<th>Material</th>
<th>Epsilon Radiation</th>
<th>$h_{\text{Conv.}}$ (W/m²K)</th>
<th>Surrounding Fluid</th>
<th>Studied Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>Tsai</td>
<td>Water</td>
<td>Reference case</td>
</tr>
<tr>
<td>2</td>
<td>$O_{\text{exp}}$</td>
<td>mild</td>
<td>0.85</td>
<td>Tsai</td>
<td>Water</td>
<td>Material</td>
</tr>
<tr>
<td>3</td>
<td>$O_{1/2}$</td>
<td>304L</td>
<td>0.85</td>
<td>Tsai</td>
<td>Water</td>
<td>Arc Heat</td>
</tr>
<tr>
<td>4</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>0</td>
<td>Water</td>
<td>Heat Loss</td>
</tr>
<tr>
<td>5</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>400</td>
<td>Water</td>
<td>Convection</td>
</tr>
<tr>
<td>6</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>1000</td>
<td>Water</td>
<td>Convection</td>
</tr>
<tr>
<td>7</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>6000</td>
<td>Water</td>
<td>Convection</td>
</tr>
<tr>
<td>8</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>0</td>
<td>Water</td>
<td>Heat Loss</td>
</tr>
<tr>
<td>9</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>0</td>
<td>Water</td>
<td>Surrounding Fluid</td>
</tr>
<tr>
<td>10</td>
<td>$O_{\text{exp}}$</td>
<td>304L</td>
<td>0.85</td>
<td>$h(T)$</td>
<td>Air</td>
<td></td>
</tr>
</tbody>
</table>
where \( Q \) is the total heat input into the workpiece, \( q_o \) is the volumetric energy generation rate, \( r_o \) is the radius of the heat input distribution, and \( d \) is the exponential factor.

By solving Equation 13, an estimation for the arc heat source is expressed as (Ref. 27)

\[
Q = q_o \int_0^r \alpha e^{\frac{\alpha^2}{2}} \, 2\pi dr \tag{13}
\]

where \( rb \) is the radius of welding conical shape, \( \upsilon \) is the electrode linear velocity, \( I \) is the current magnitude, \( V \) is the potential difference, and \( \eta \) is the electrical arc efficiency. A rougher estimation for the arc heat source relation is

\[
Q = \frac{A_v A_i}{2\pi \eta v} \tag{15}
\]

where \( A_v \), \( A_i \), \( A_r \), and \( \eta_a \) are the arc voltage, arc current, arc radius (approximately equal to electrode radius), and arc efficiency, respectively.

The temperature distributions within the weldment were measured continuously throughout the welding process considering 22 points where temperature was calculated by the developed simulation code. The positions of these points are shown in the XY plane in Fig. 2. Points numbered 1 to 11 are at the surface of the plate along a line parallel to the weld interface (i.e., along the Y direction) and points numbered 12 to 22 are in the middle thickness of the plate, vertically located to the weld interface (i.e., along the X direction).

Table 5 — The Assumed Model Parameters

<table>
<thead>
<tr>
<th>Initial Temp (K)</th>
<th>( \text{W/m}^2\text{K}^4 )</th>
<th>I (A)</th>
<th>Voltage (V)</th>
<th>rb (m)</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>298</td>
<td>5.6697E–8</td>
<td>0.53</td>
<td>200</td>
<td>23</td>
<td>2.5 \times 10^{-3}</td>
</tr>
</tbody>
</table>
Results and Discussion

Welding Thermal Analysis in Air

In Fig. 3, the finite difference simulation results for the weldment temperature history at points with different distances from the weld interface are compared with the experimental findings by Attarha and Sattari-Far (Ref. 17), as described in the model validation section.

As can be observed, the calculated results conform well with the experimental results and the rate of the temperature changes has a similar trend as in the experimental case in all three studied points. Consequently, the model can be used to simulate and predict the wet underwater welding heat transfer phenomenon in subsequent steps in this work.

Underwater Thermal Analysis

Material Selection

As shown in Table 5, the simulated cases 1 and 2 illustrate the effect of the material type in underwater welding. The maximum temperature of the plate during welding has been calculated and is shown in Fig. 4A, B. As evidenced in these figures, the maximum temperatures along the vertical line to the welding path are similar for both mild steel and 304 stainless steel. It is the high convective heat loss in water welding media that causes the rapid cooling, and consequently the difference between two metals could not be distinguished. This effect is also presented in the parallel line, but because of the electrode motion, a small difference can be seen between the two materials.

The rapid cooling in water does cause a significant difference between the cooling times for Type 304 stainless steel and mild steel, and as a result, the obtained cooling time is 43.42 s for Type 304 stainless steel and 43.74 s for mild steel. The temperature history of two points, 10 and 17, are drawn in plots 5A and 5B, respectively. It is observed that the thermal histories at a point along the parallel direction to the weld interface are the same for the two studied steels, where the curve is material dependent for the points on the vertical line to the welding path.

The Effect of the Surrounding Fluid

To study the effect of the surrounding fluid on the weldment, case 10 was carried out in air in comparison with case 1 in water, where the other parameters were considered to be the same. The thermal history for the first and end points on the vertical and parallel lines to the welding path are shown in plots 6A–D.

As observed in these plots, the temperatures of all points are higher for the air case in comparison to the water case. As shown in plot 6D, it is observed that the thermal curve of point 22 in the plate far from the weld interface, is a constant line when the
plate is in the water. Therefore, the type of surrounding fluid type affects the welding process and the resulting temperatures, significantly. This effect is because of the much greater convective heat transfer coefficient \( (h_c) \) of water in comparison with the air, hence a rapid cooling phenomenon and lower temperatures occur during underwater welding. In a fluid such as water that has a large \( h_c \) value, a thermal history trend results only for points on the weld interface or near it, because the convective heat transfer is much greater than the arc heat source at far distances from the weld path.

The local maximum temperatures in the vertical direction are shown in Fig. 7A, B after 20 s and 40 s in the air and water fluids. It is observed that after 40 s, the plate in water has completely cooled, while the plate in air has not yet cooled. The calculated overall cooling times are much different as the cooling time for air is 1163.7 s, compared to the water case, which is equal to 43.4 s. This effect is also due to the much different values of \( h_c \) in air and water.

### The Effect of Convective Heat Transfer Coefficient

The effect of \( h_c \) value was investigated through case studies 1 and 5–7. In case 1, the Tsai estimation is used to predict the \( h_c \) value. The \( h_c \) value is assumed constant and equal to 400, 1000, and 6000 W/m²K in cases 5, 6, and 7, respectively. Figure 8 shows the temperature profile in the vertical direction after several time intervals.

It is observed that the resulting plots are almost similar when the Tsai estimation is used or \( h_c \) is set at 6000 W/m²K. Also, for the \( h_c \) values ranging from 400 to 1000 W/m²K, the plots are almost similar to each other. It is seen that the Tsai model is an approximate formulation for the \( h_c \) and can be used properly when the \( h_c \) is between 1000 and 6000 and is closer to the 6000 W/m²K. The ultimate cooling times for the plate are summarized in Table 7. The thermal history curves at points 2, 10, 13, and 18 are presented in plots 9A–D. It can be concluded that the maximum achieved temperature for points 2, 10, and 13 are similar and are in the range of 4400–4900 K. However, the maximum temperature reached for point 18 is 518 K, which is much lower than the other three studied points. It seems that, because point 18 is far from the weld interface in comparison to the other three points, the heat loss by convection acts stronger than the arc heat source and thus this point cannot reach greater maximum temperatures.

### The Effect of the Arc Heat Estimation

It was previously explained that a precise solution for the arc heat model is an exponential form of Equation 11 that is applied in the current study for modeling the underwater welding process. To investigate the effect of the type of arc heat model used in the simulation method, a simpler but less precise model as the exponential form is used in Case 3, as described in Equation 15. The maximum temperatures along the lines vertically and parallel to the weld interface are calculated, where Case 1 is assumed as the reference case and case 3 is compared against it. The error percentages of the absolute temperatures resulting from solving Case 3, relative to Case 1, are reported in Fig. 10.

In the short distances along the vertical direction to the welding path, there is a distinct difference between the resulting temperatures from the two models. In the meantime, there is no considerable difference between the two arc heat models in the parallel direction to the weld interface, except for the first point. Therefore, \( Q_{1/2} \) model could not be as accurate as the \( Q_{exp} \) model in the HAZ or the local temperature calculations especially in the vertical direction. However, if an overall and not local result or thermal history is desired, there is no particular difference between either of these models.

### The Effect of Heat Transfer Type

The effect of convection and radiation heat transfer terms and their contributions to the energy model are studied through Cases 1, 4, 8, and 9. In these case studies, temperature history curves are obtained for points 3, 9, and 15 on the plate shown in Fig. 11. In Case 1, both convection and radiation terms are considered in the model. The value of \( h_c \) is assumed to be zero in Case 4, but radiation heat loss is the former. Case 8 includes the convection term while radiation is assumed negligible and, finally, both heat loss terms are set at zero in Case 9.

The cooling times and final temperatures of the plate for all considered situations are reported in Table 8.

Notice that the cooling times for Cases 1 and 8 are almost the same and are the lowest. This observation shows that although the radiation is removed in case 8, but it has no significant role in the cooling time and the thermal history curve. The convection is more effective and much greater than the radiation in temperature calculations and the radiation term is negligible in the heat transfer model. When both convection and radiation terms are withdrawn from the energy equation, the plate could not be cooled to that of the surrounding temperature and all the points become isothermal at 457 K after 524 s. This situation is due to the fact there is no way for the plate to cool.

### Conclusion

A three-dimensional heat transfer model was developed to study underwater welding of thin steel plates. The exponential estimation for the arc heat formulation was used in the modeling procedure.
Tsai’s and Masubuchi’s semi-empirical correlation, defining the surface heat transfer coefficient of the underwater weldments, was used to determine the heat loss through the surface of the welded plate. The explicit form of the finite difference method (FDM) was used to solve the energy equation. The computed results were compared against the experimental data to ensure that the modeling and solution method are reliable.

The effect of the modeling parameters including the material type, the type of the surrounding fluid, the convective heat transfer coefficient \( h_c \) value, the arc heat model, and how heat is lost from the plate were investigated through ten case studies.

Two steel type characteristics were used to study the material effect in wet welding. However, it seems the material effect could not be distinguished obviously in the underwater welding because of the rapid cooling phenomenon. The effect of the fluid was studied by comparing the thermal histories and the temperature distribution in the water and air environments. The results showed that the fluid type has a considerable effect in the welding process, and as a result, the plate is cooled much more rapidly in water in comparison with the air. The efficacy analysis of \( h_c \) was performed via four case solutions using the Tsai model and three constant values of \( h_c \) in the energy equation. The obtained results demonstrated that the Tsai model can predict \( h_c \) successfully when its value is between 1000 and 6000 W/m\(^2\)K, especially when it is closer to 6000 W/m\(^2\)K. The arc heat estimation was investigated using a simpler estimation noted by \( Q_{1/2} \) in comparison with the exponential form. It was concluded that, when the temperature distribution in short vertical distances from the weld interface is considered, the \( Q_{1/2} \) model is not as precise as the \( Q_{exp} \) model, while there is no difference between the two used arc heat estimations at the other positions.

The analysis of the curves resulted from four different situations considering and/or ignoring the convection/radiation terms was also carried out. It was shown that the convective heat transfer is more effective in temperature calculations compared with radiation, hence the radiation can be considered negligible in the energy equation.

**References**

8. Eyres, D. J., and Bruce, G. J. 2012. Ship Construction, Chapter 9: Welding and cutting processes used in shipbuilding, Butterworth-
Heinemann, pp. 75–96.