Simplified Mathematical Modeling of Implant Limit Stress and Maximum HAZ Hardness

Models were developed to form a simple, accessible tool for use in assessing susceptibility to hydrogen-induced cracking in steel weldments

BY A. FOTOUGH, M. EL-SHENNAWY, AND R. EL-HEBEARY

ABSTRACT

Hydrogen-induced cracking (HIC) susceptibility in the heat-affected zone (HAZ) was investigated and modeled using implant static tensile limit stress ($\sigma_{imp}$) and maximum hardness of the HAZ ($HV_{10MAX}$). C-Mn and high-strength low-alloy (HSLA) steels were used as base metals with a carbon equivalent (CE) ranging from 0.38 to 0.48% and 0.52 to 0.69%, respectively. The shielded metal arc welding (SMAW) and gas metal arc welding (GMAW) processes with CO2 shielding gas were used. The diffusible hydrogen ($H$) content was varied taking the values between 2 and 40 mL/100 g. $\sigma_{imp}$ and $HV_{10MAX}$ were the two measures used to evaluate the weldment susceptibility to HIC. Using Pearson’s product-moment coefficient ($P_{pm}$) and the developed analysis of HIC susceptibility, two simplified models were developed using simple mechanistic models, linear and logarithmic, to simulate $\sigma_{imp}$ and $HV_{10MAX}$ as functions of welding parameters or factors (i.e., $H$, carbon content), and 2) the weld cooling time between 800° and 500°C ($t_{800/500}$) at which the austenitic transformations take place. Hydrogen-induced cracking susceptibility is increased by increasing HAZ hardness (Refs. 1–4, 9, 12–16).

Therefore, this present study was concerned with analyzing and modeling $\sigma_{imp}$ and $HV_{10MAX}$ as they both form the main factors that can be used to assess susceptibility to HIC in steel weldments (Refs. 1–4, 11–16). Simplified models were developed to estimate the values of $\sigma_{imp}$ and $HV_{10MAX}$ as functions of welding factors (i.e., CE, $t_{800/500}$, and $H$).

Testing Materials and Procedures

The designations of the tested steels and their mechanical properties are shown in Table 1. The Dearden and O’Neill equation, represented in Equation 1, was applied to calculate the CE for each one of the tested steels (Refs. 17–19). This equation is used for steels with carbon contents greater than 0.12%, and if the calculated CE is greater than 0.35%, special precautions should be considered to prevent HIC (Ref. 17). The Dearden and O’Neill equation is the formula used by the International Institute of Welding (IIW) to evaluate carbon equivalent (Ref. 20).

$$CE = C + (Mn)/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$$

(1)

The calculated CE values are shown in Table 2. The tested base metals are divided into two main categories of steels:
1. C-Mn steels, which have CE values in the range of 0.38 to 0.48% and yield strength values in the range of 350 to 623 MPa.
2. High-strength, low-alloy (HSLA) steels, which have CE values in the range of 0.52 to 0.69% and yield strength range
between 295 and 710 MPa. Different welding electrodes were used in this research using two welding processes: shielded metal arc welding (SMAW) and gas metal arc welding (GMAW) with CO₂ as a shielding gas. The mechanical properties of the deposited weld metal are shown in Table 1, while its chemical composition is given in Table 2, according to the designations of JIS Z 3113, JIS Z 3117, and DIN 8572 Part I (Ref. 19). Table 3 shows the designation of the electrodes used along with their chemical composition and the mechanical properties of the deposited weld metal.

Using the glycerin displacement method, the diffusible hydrogen content was measured for each electrode type (Ref. 19). The procedures followed in the glycerin method were according to the designations of JIS Z 3113, JIS Z 3116, JIS Z 3117, and DIN 8572 Part I (Ref. 19). Table 3 shows the designation of the electrodes used under the conditions in Table 1, which were the conditions the manufacturer recommended.

Figure 1 shows the applied implant test procedures with a 150-mm weld bead on the backing plate and the applied implant load. For each implant test, a 6.0±0.02-mm diameter hole was drilled in a backing plate (Ref. 19). The backing plate was manufactured in two thicknesses of 10 and 30 mm simulating 2-D and 3-D weldments. The backing plate steel designation and mechanical properties are listed in Table 1, while its chemical composition is listed in Table 2.

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Figure 1 shows the applied implant test procedures with a 150-mm weld bead on the backing plate and the applied implant test procedures are as follows:

1. The implant test is inserted into the backing plate hole.
2. When the electrode reaches the tip of the implant test specimen, cooling time is started to be counted.
3. The implant load is started to be applied when the temperature is 150°C, while the full applied implant load is reached when the temperature is 100°C.
4. The implant specimen is fractured within 24 h depending on the amount of the applied implant load.
5. If the implant specimen is not fractured after 24 h under a certain implant load, the corresponding stress to this load will be the implant static tensile limit stress (σ_{imp}). To ensure that the stress value reached was the value of σ_{imp}, five more specimens were tested at this stress value. The stress is considered to be σ_{imp} if the five tested specimens are not fractured after 24 h.

The cooling time from 800°C to 500°C (t_{800/500}) was measured using a thermocouple that was implanted into the backing plate in the same way the implant test specimen pins were implanted. The measured values of t_{800/500} are shown in Table 5. In order to incorporate t_{800/500} into the developed mathematical models and to consistently control the loading time of implant tests, a heat transfer thermal model was used to simulate the measured values of t_{800/500} based on the applied welding conditions. Additionally, the use of the heat transfer model ensures that the developed mathematical models are a fully mathematical engineering tool that can be used directly to estimate the values of σ_{imp} and the values of HV_{10MAX} without the need to take any further measurements.

Rosenthal’s heat transfer models are usually used to estimate the weldment’s cooling cycle (Refs. 3, 21, 22). For a radial distance near the weld, Adam’s heat transfer models can be developed from Rosenthal’s models (Ref. 19); therefore, Adam’s models can be used to estimate the cooling time of the HAZ coarsened grain region near the weld (Refs. 9, 19, 21, 23). In this study, the Adam’s heat transfer models

![Fig. 1 — Schematic representing the applied implant test procedures.](image1)

![Fig. 2 — Sections of implant test specimen pins: A — Nonfractured; B — fractured.](image2)

**Table 1 — Mechanical Properties for Base Metals**

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>Base Metal Sample</th>
<th>Steel Designation</th>
<th>Yield Strength, MPa</th>
<th>Mechanical Properties</th>
<th>Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-Mn</td>
<td>A</td>
<td>DIN: 17Mn4</td>
<td>350</td>
<td>580</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>DIN: St 52-3N</td>
<td>420</td>
<td>595</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>MSZ: E420C</td>
<td>623</td>
<td>775</td>
<td>21</td>
</tr>
<tr>
<td>HSLA</td>
<td>D</td>
<td>MSZ:KL3</td>
<td>295</td>
<td>535</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>ASTM:387-G11</td>
<td>310</td>
<td>585</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>DIN:20CrMo5</td>
<td>710</td>
<td>1150</td>
<td>7</td>
</tr>
<tr>
<td>Implant backing plate (heat sink)</td>
<td></td>
<td>DIN: St 37-2</td>
<td>260</td>
<td>320</td>
<td>54</td>
</tr>
</tbody>
</table>

![Image](image3)
were used to calculate the cooling time from 800° to 500°C (t800/500), which is a very critical cooling time at which the austenitic microstructure transformations are characterized (Ref. 24). Adam’s heat transfer model for a 3-D heat flow (i.e., for a thick plate) can be represented as in Equation 2, while Equation 3 can be used to calculate the cooling time for a 2-D heat flow (i.e., for a thin plate) (Refs. 21, 23). If the implant test heat sink (i.e., backing plate) is thinner than the critical thickness, it is a 3-D heat flow; on the other hand, if the heat sink is thicker than the critical thickness, it is a 2-D heat flow (Refs. 21, 23).

\[ t_{T1/T2} = \frac{[E f v m]}{2\pi k} \left( \frac{T_1 - T_2}{(T_2 - T_0) - (T_1 - T_0)} \right) \]

where \( t_{T1/T2} \) is the cooling time (s) from \( T_1 \) to \( T_2 \) at initial plate temperature \( T_0 \) (for \( t_{800/500} \): \( T_1 = 800°C, T_1 = 500°C,\) and \( T_0 = 25°C \)). \( E \) is the arc voltage (V), \( v \) is the welding speed (mm/s), \( f \) is the arc efficiency (f = 80% for SMAW and GMAW processes (Ref. 23)), \( m \) is a constant related to the weld joint (1 for bead on plate, \( \frac{2}{3} \) for T-joint (Ref. 23)), and \( k \) is the thermal conductivity of the metal (\( k = 0.028 \) J.mm−1.S−1.C−1 for DIN: St 37-2 (Ref. 23)).

\[ t_{T1/T2} = \frac{[E f v m]}{2\pi k} \left( \frac{T_1 - T_2}{(T_2 - T_0) - (T_1 - T_0)} \right) \]  

where \( S_c \) is the critical thickness.

Table 5 shows both the calculated and measured values of \( t_{800/500} \) at different applied welding conditions used during the implant tests. The Adam’s model results for 2-D heat flow were slightly higher than the measured values of \( t_{800/500} \); this can be attributed to diminishment of the effect of the surface heat transfer in the 2-D flow of the Adam’s model. However, there is still a close similarity between the measured and calculated values of \( t_{800/500} \). Additionally, by applying the coefficient of determination (R²), the goodness of fit for the linear relationship between the measured and calculated values of \( t_{800/500} \) for the 3-D (i.e., thick plate) heat flow was 0.97, and it was 0.99 for 2-D (i.e., thin plate) heat flow. Therefore, it can be concluded that Adam’s model is highly suited for evaluating the cooling time between 800° and 500°C \( (t_{800/500}) \) for implant test procedures.

For steels with estimated yield strength between 350 and 600 MPa, HIC in HAZ forms the majority of the cracks developed by hydrogen embrittlement, especially with electrodes having low carbon contents (Refs. 4, 6, 12, 13). Additionally, weldments with unmatched weld metal strength are most likely to have HIC in the HAZ (Refs. 4, 26). The base metals and consumables were selected to ensure that HIC is more likely to occur in the base metal; the HAZ coarsened grain region was the area at which hardness was measured because the

Table 2 — Chemical Composition and Carbon Equivalent for Base Metals

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>Base Metal Sample</th>
<th>Chemical Composition, %</th>
<th>CE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>C-Mn</td>
<td>A</td>
<td>0.130</td>
<td>0.241</td>
</tr>
<tr>
<td>B</td>
<td>0.148</td>
<td>0.266</td>
<td>1.380</td>
</tr>
<tr>
<td>C</td>
<td>0.210</td>
<td>0.450</td>
<td>1.250</td>
</tr>
<tr>
<td>HSLA</td>
<td>D</td>
<td>0.220</td>
<td>0.210</td>
</tr>
<tr>
<td>E</td>
<td>0.118</td>
<td>0.505</td>
<td>0.528</td>
</tr>
<tr>
<td>F</td>
<td>0.198</td>
<td>0.188</td>
<td>1.060</td>
</tr>
<tr>
<td></td>
<td>Implant backing</td>
<td>0.063</td>
<td>0.181</td>
</tr>
</tbody>
</table>

Fig. 3 — Effect of H on the implant test results for steel B: 0.42 (CE) and at \( t_{800/500} \) at 4.5 s.

Fig. 4 — Effect of H on the implant tests results for steel E: 0.58 (CE) at \( t_{800/500} \) at 4.5 s.
susceptible HAZ microstructure is expected to be developed in this region (Ref. 27). Figure 2A shows a section through a nonfractured implant pin, while Fig. 2B depicts how the fracture occurred in the implant test specimen within the HAZ coarsened grain region near the weld.

Hardness tests were carried out using a Vickers hardness tester with a 10-kg load (Ref. 19). The hardness was measured in the coarsened grain region of the HAZ on a line tangent to the weld fusion zone. The hardness measurement procedures were applied according to IIW procedures with a 1-mm interval distance between indentations (Refs. 19, 28).

Results Discussion and Modeling

The three major welding factors affecting \( \sigma_{\text{imp}} \) and \( \text{HV}_{10\text{MAX}} \) are as follows (Refs. 1–4, 19): 1) the cooling time between 800° and 500°C (\( t_{800/500} \)); 2) the base metal carbon equivalent (CE); and 3) the diffusible hydrogen content (H). There are some other minor factors that also affect the values of \( \sigma_{\text{imp}} \) and \( \text{HV}_{10\text{MAX}} \) (i.e., the susceptibility to HIC), such as the carbon content and the yield strength (Refs. 4, 6, 12, 13, 29); however, the present study focuses on the three major effective factors (i.e., \( t_{800/500} \), CE, and H) and their effect on \( \sigma_{\text{imp}} \) and \( \text{HV}_{10\text{MAX}} \). In this study, these three major effective factors were considered the essential variables that were used to develop the mathematical models for both \( \sigma_{\text{imp}} \) and \( \text{HV}_{10\text{MAX}} \).

The following part is divided into two main sections: the first section, assessment of HIC susceptibility, is to demonstrate the observed effects of \( t_{800/500} \), CE, and H on \( \sigma_{\text{imp}} \) and \( \text{HV}_{10\text{MAX}} \); the second section, modeling of HIC susceptibility, is to illustrate how these three welding factors (i.e., \( t_{800/500} \), CE, and H) are interactively integrated to affect \( \sigma_{\text{imp}} \) and \( \text{HV}_{10\text{MAX}} \); additionally, the second section discusses how to incorporate the interactively integrated effect of the three major welding factors into simplified mathematical models developed to simulate \( \sigma_{\text{imp}} \) and \( \text{HV}_{10\text{MAX}} \).

Assessment of HIC Susceptibility

Figures 3 and 4 show implant stress-time curves that indicate the effect of different values of the diffusible hydrogen content (H) on the implant test results for both C-Mn steel with CE of 0.42 and HSLA steel with CE of 0.58, respectively, at \( t_{800/500} \) of 4.5 s. The first part of these implant stress-time curves was developed as a result of the different stresses that were applied until the implant limit stress (\( \sigma_{\text{imp}} \)) was reached, which is represented by the horizontal lines in the curves. The logarithmic regression was used to plot the linear relationship in the first part of the implant stress-time curves. These developed linear relationships were plotted not to represent any physical property except the general trend of the first part of the implant stress-time curves (i.e., to demonstrate that the time to fracture increased by decreasing the applied static stress). R² values in Figs. 3 and 4 represent the goodness of fit of the logarithmic regression used to plot the first part of the curves. The horizontal lines in Figs. 3 and 4 demonstrate that the value of \( \sigma_{\text{imp}} \) decreases by increasing H, and this increases the risk of HIC at a constant value of \( t_{800/500} \). Using the logarithmic regression, Figs. 5 and 6 show the relationship between \( \sigma_{\text{imp}} \) and H for both C-Mn and HSLA steels, respectively, at different values of CE and \( t_{800/500} \). Generally, Figs. 5 and 6 illustrate that at certain \( t_{800/500} \) and CE when the value of H decreases, the value of \( \sigma_{\text{imp}} \) increases, and this reduces the susceptibility to HIC.

The implant test results for both C-Mn steel with CE of 0.42 and HSLA steel with CE of 0.58 were plotted at H of 30 mL/100
Welding and different values of $t_{800/500}$, as shown in Figs. 7 and 8, respectively. As depicted in Figs. 7 and 8, when the cooling time between 800° and 500°C ($t_{800/500}$) increased, the implant static tensile limit stress ($\sigma_{\text{imp}}$) increased, lessening the susceptibility to HIC. The same result can be concluded from Figs. 9 and 10, which show the $\sigma_{\text{imp}}- t_{800/500}$ relationship conducted by the logarithmic regression for both C-Mn and HSLA steels, respectively, at different values of CE and H. Figure 11A–C shows how $t_{800/500}$ affects the development of the susceptible HAZ microstructure. Figure 11A shows a ferrite pearlite hot-rolled microstructure of the base metal A: 0.38% CE (Ref. 19). This microstructure was transformed into a Widmanstätten ferrite microstructure in the HAZ of the implant test specimen at $t_{800/500}$ value of 4.5 s (Ref. 19), as shown in Fig. 11B. In Fig. 11C, as $t_{800/500}$ increased to 16.5 s, the ferrite pearlite base metal structure was transformed into a refined acicular ferrite with a cleavage shape structure (Ref. 19). This change in the HAZ microstructure from the Widmanstätten ferrite to the acicular ferrite reduced HV$_{10\text{MAX}}$ from 385 to 330, and increased the implant static tensile limit stress ($\sigma_{\text{imp}}$) from 450 to 565 MPa, respectively, at H of 2 mL/100 g (Ref. 19).

Figures 12 and 13 indicate the effect of carbon equivalent (CE) on the results of the implant test at $t_{800/500}$ of 9.3 s for C-Mn steels and at $t_{800/500}$ of 6.3 s for HSLA steels, respectively, at H of 40 mL/100 g. Decreasing CE values caused an increase in the measured values of the implant static tensile limit stress ($\sigma_{\text{imp}}$), as shown by the horizontal lines in Figs. 12 and 13. The same behavior is confirmed through Figs. 14 and 15, as the linear regression was used to show the relationship between $\sigma_{\text{imp}}$ and carbon equivalent (CE) for both C-Mn and HSLA steels, respectively, at different values of $t_{800/500}$ and H. Therefore, as concluded from Figs. 12–15, $\sigma_{\text{imp}}$ decreases by increasing CE, which promotes the susceptibility to HIC.

Using the logarithmic regression, Figs. 16 and 17 represent the relationship between HV$_{10\text{MAX}}$ and $t_{800/500}$ for C-Mn and HSLA steels, respectively, at different values of CE. The maximum HAZ hardness (HV$_{10\text{MAX}}$) was increased by decreasing the cooling time between 800° and 500°C ($t_{800/500}$). On the other hand, decreasing CE caused HV$_{10\text{MAX}}$ to decrease at a certain $t_{800/500}$ as depicted in Figs. 18 and 19, using the linear regression, for C-Mn and HSLA steels, respectively.

### Modeling of HIC Susceptibility

Cooling time between 800° and 500°C ($t_{800/500}$) and carbon equivalent (CE) influence the microstructure ability to produce a certain maximum HAZ hardness (HV$_{10\text{MAX}}$), which consequently can be used to assess the developed microstructure in HAZ (Refs. 4, 12–16). Therefore, HV$_{10\text{MAX}}$ can be assumed to be the reason by which $t_{800/500}$ and CE affect $\sigma_{\text{imp}}$. Hence, it can be concluded that the main welding factors affecting $\sigma_{\text{imp}}$ are the maximum HAZ hardness (HV$_{10\text{MAX}}$), and the diffusible hydrogen content (H). On the other hand, the welding factors affecting HV$_{10\text{MAX}}$ are the cooling time between 800° and 500°C ($t_{800/500}$), and the carbon equivalent (CE).

To develop the models that predict the values of $\sigma_{\text{imp}}$ and HV$_{10\text{MAX}}$, the effect of each welding factor on $\sigma_{\text{imp}}$ and HV$_{10\text{MAX}}$...
have to be evaluated. Pearson’s product-moment coefficient ($P_{pm}$) can provide an indication of the dependency or independency of two numerical values with regard to each other (Refs. 30–32). Therefore, Pearson’s product-moment coefficient ($P_{pm}$) can be used as a tool to identify the dominating welding factor affecting either $\sigma_{imp}$ or $HV_{10MAX}$ by evaluating the dependency of $\sigma_{imp}$ and $HV_{10MAX}$ on each welding factor that affects each one of them. Equation 5 represents the statistical function used to calculate $P_{pm}$ (Ref. 33).

$$P_{pm}(x, y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where $P_{pm}(x, y)$ is Pearson’s product-moment coefficient for two numerical parameters (i.e., $x$ and $y$), $n$ is the number of readings for parameters $x$ and $y$, $\bar{x}$ is the average of parameter $x$ readings, $\bar{y}$ is the average of parameter $y$ readings, and $i$ is the counter of the readings number $n$.

$P_{pm}$ can take values from 1.00 to –1.00. At $P_{pm} = 1.00$, there is a perfect direct correlation between the two numerical parameters. At $P_{pm} = 0.00$, there is no correlation at all between the numerical parameters. For $P_{pm} = –1.00$, there is a perfect inverse correlation between the two numerical parameters.

As illustrated previously, the main welding factors controlling $\sigma_{imp}$ can be considered to be the maximum HAZ hardness ($HV_{10MAX}$) and the diffusible hydrogen content ($H$). Table 6 shows the values of $P_{pm}$ between $\sigma_{imp}$ and its controlling welding factors (i.e., $HV_{10MAX}$ and $H$) for the tested C-Mn steels and HSLA steels. For C-Mn steels (i.e., CE: 0.38 to 0.48), the values of $P_{pm}$ for the $\sigma_{imp}$-$HV_{10MAX}$ relationship are relatively high, which means that $HV_{10MAX}$ is the dominating welding factor affecting $\sigma_{imp}$, and the negative sign is a result of the inverse correlation between $HV_{10MAX}$ and $\sigma_{imp}$. However, the dominating effect of $HV_{10MAX}$ over $\sigma_{imp}$ was reduced for HSLA steels (i.e., CE: 0.52 to 0.69), and $H$ became the dominating welding factor that affected $\sigma_{imp}$; therefore, it can be concluded that the HIC susceptibility for the HSLA steel category is mainly dominated by the diffusible hydrogen content ($H$). This could be attributed to the relatively heavy existence of some alloying elements in the composition of HSLA steels. These alloying elements increase the effect of the diffusible hydrogen content ($H$) on the susceptibility to HIC. To illustrate, the vanadium ($V$) percentage in steel D (CE: 0.52) was relatively high ($V$: 0.13%) compared to the vanadium percentage in other steels. The increase in the vanadium percentage promoted the amount of the absorbed hydrogen for a given value of the diffusible hydrogen content ($H$) (Ref. 34); therefore, the effect of the diffusible hydro-
gen content (H) on the susceptibility to HIC was increased; additionally, the percentage of other alloying elements such as nickel (Ni) in the same D (CE: 0.52) steel was relatively a high percentage (Ni: 0.7%), and this increased the amount of the absorbed hydrogen (Refs. 35, 36). For other HSLA steels, the relatively high percentage of chromium (Cr) and molybdenum (Mo) in both steel E (CE: 0.58) and steel F (CE: 0.69) acted interactively to increase the susceptibility to HIC as a result of increasing the diffused hydrogen (Ref. 20). However, from Table 6, as the CE range was increased to include both C-Mn steels and HSLA steels (i.e., for the overall CE range from 0.38 to 0.69), HV10MAX can be considered as the overall dominating welding factor that affects $\sigma_{imp}$ in steel weldments. The overall values of $P_{pm}$ for HV10MAX are relatively high ($P_{pm} = -0.71$); therefore, a linear mechanistic model can be proposed to simulate the relationship between $\sigma_{imp}$ and HV10MAX as follows:

$$\sigma_{imp} = \alpha + \beta HV_{10MAX}$$  \(6\)

where $\alpha$ and $\beta$ are parameters assumed to be functions of the diffusible hydrogen content (H).

Figures 5 and 6 show the relationship between $\sigma_{imp}$ and H could be represented using a logarithmic model. Therefore, the parameters $\alpha$ and $\beta$ in Equation 6 could be represented as a function of H using the logarithmic model shown in Equations 7 and 8, respectively.

$$\alpha = \alpha_a + \alpha_b \ln(H)$$  \(7\)

where $\alpha_a$ and $\alpha_b$ are base metal parameters.

$$\beta = \beta_a + \beta_b \ln(H)$$  \(8\)

where $\beta_a$ and $\beta_b$ are base metal parameters.

From Equations 6–8, the developed model of $\sigma_{imp}$ can be represented as follows:

$$\sigma_{imp} = \alpha_a + \beta_a HV_{10MAX} + \ln(H)$$  \(9\)

$$\alpha_a + \beta_a HV_{10MAX}$$

where $\sigma_{imp}$ is the implant static tensile limit stress, HV10MAX is the maximum HAZ hardness, H is the diffusible hydrogen content, $\alpha_a$ and $\alpha_b$ are the base metal parameters in Equation 7, and $\beta_a$ and $\beta_b$ are the base metal parameters in Equation 8.

Using Levenberg-Marquardt, a modified version of the Gauss-Newton method (Ref. 37), the optimized solutions for the developed model parameters in Equation 9 were calculated. Table 7 shows the optimized solutions of the parameters $\alpha_a$, $\alpha_b$, $\beta_a$, and $\beta_b$ in Equation 9 for the categories of tested steels.

Using the parameter values in Table 7, Figs. 20–22 were plotted showing that the values of $\sigma_{imp}$ calculated by the developed model ($\sigma_{impC}$), in Equation 9, closely match.

![Fig. 11 — Microstructure images of (Ref.19): A — The C-Mn steel A: 0.38 CE base metal; B — a Widmanstätten ferrite in the coarsened grain HAZ region at t800/500 of 4.5 s; and C — an acicular ferrite in the HAZ coarsened grain region at t800/500 of 16.5 s.](image1.png)

![Fig. 12 — Effect of base metal CE on the results of the implant test for steels A: 0.38 (CE), B: 0.42 (CE), and C: 0.48 (CE) at H of 40 mL/100 g and t800/500 of 9.3 s.](image2.png)

![Fig. 13 — Effect of base metal CE on the results of the implant test for steels D: 0.52 (CE), E: 0.58 (CE), and F: 0.69 (CE) at H of 40 mL/100 g and t800/500 of 6.3 s.](image3.png)
the values of $\sigma_{\text{imp}}$ measured from the implant tests ($\sigma_{\text{imp}}$) for CE ranges of 0.38–0.48 (i.e., C-Mn steels), 0.52–0.69 (i.e., HSLA steels), and 0.38–0.69 (i.e., both C-Mn and HSLA steels), respectively.

The second parameter that can be used to assess HAZ susceptibility to HIC is the maximum HAZ hardness (HV$_{10\text{MAX}}$), which is affected by $t_{800/500}$ and CE (Refs. 1–4, 19). Table 8 shows the values of Ppm for HV$_{10\text{MAX}}$–t$_{800/500}$ and HV$_{10\text{MAX}}$–CE relationships. For both the C-Mn steels category (with CE ranging between 0.38 and 0.48) and HSLA steels category (with CE ranging between 0.52 and 0.69), the dominating welding factor affecting HV$_{10\text{MAX}}$ is $t_{800/500}$, as shown in Table 8. By increasing the CE domain to cover the range between 0.38 and 0.69, the Ppm for the HV$_{10\text{MAX}}$–t$_{800/500}$ relationship was lowered to –0.45. This can be attributed to the lack of linearity in the HV$_{10\text{MAX}}$–t$_{800/500}$ relationship, as shown in Figs. 16 and 17. On the other hand, the Ppm for HV$_{10\text{MAX}}$–CE increased to –0.70, which can be attributed to the linearity in the relationship between HV$_{10\text{MAX}}$ and CE, as shown in Figs. 18 and 19. Therefore, t$_{800/500}$ can still be assumed to be the dominating welding factor affecting HV$_{10\text{MAX}}$ for both C-Mn and HSLA steels. For C-Mn and HSLA steels, the relationship between t$_{800/500}$ and HV$_{10\text{MAX}}$ is a logarithmic relationship, as shown in Figs. 16 and 17, respectively; therefore, the relationship between t$_{800/500}$ and HV$_{10\text{MAX}}$ can be represented using a logarithmic mechanistic model as follows:

$$HV_{10\text{MAX}} = \xi + \psi \ln(t_{800/500})$$ (10)

where $\xi$ and $\psi$ are parameters that can be considered as functions of carbon equivalent (CE).

Figures 18 and 19 show a linear relationship between CE and HV$_{10\text{MAX}}$; therefore, $\xi$ and $\psi$, assumed to be a function of CE in Equation 10, can be represented in linear relationships with CE as in Equations 11 and 12, respectively.

$$\xi = \xi_a + \xi_bCE$$ (11)

where $\xi_a$ and $\xi_b$ are base metal parameters.

$$\psi = \psi_a + \psi_bCE$$ (12)

where $\psi_a$ and $\psi_b$ are base metal parameters.

From Equations 10–12, the developed model for HV$_{10\text{MAX}}$ in Equation 10 can be rewritten as follows:

$$HV_{10\text{MAX}} = \xi_a + \xi_b \ln(t_{800/500}) + CE(\xi_a + \psi_a \ln(t_{800/500})$$ (13)

where HV$_{10\text{MAX}}$ is the maximum HAZ hardness, t$_{800/500}$ is the cooling time between 800° and 500°C, $\xi_a$ and $\xi_b$ are the base metal parameters in Equation 11,
and \( \psi_a \) and \( \psi_b \) are the base metal parameters in Equation 12.

Using the Levenberg-Marquardt method, the optimized solutions for parameters \( \xi_a \), \( \xi_b \), \( \psi_a \), and \( \psi_b \) in Equation 13 are shown in Table 9 for the tested categories of steels.

Figures 23–25 demonstrate a good match between the measured HV10MAX and the values of HV10MAX calculated using the model developed in Equation 13 for the CE ranges of 0.38–0.48, 0.52–0.69, and 0.38–0.69, respectively.

**Conclusion**

The effect of each welding factor (i.e., diffusible hydrogen content (H), cooling time between 800° and 500°C (\( t_{800/500} \)) and carbon equivalent (CE)) on HIC susceptibility was investigated. The susceptibility of HAZ to HIC was assessed using implant static tensile limit stress (\( \sigma_{imp} \)) and maximum HAZ hardness (HV10MAX). The experimental results showed that \( \sigma_{imp} \) increased, decreasing the susceptibility to HIC, by increasing \( t_{800/500} \); on the other hand, \( \sigma_{imp} \) decreased, increasing the susceptibility to HIC, by increasing CE and H. Additionally, it was shown through experimental results that HV10MAX increases by increasing CE or reducing \( t_{800/500} \), and this increases the susceptibility to HIC.

Based on the calculated values of \( P_{pm} \), the dominating factor affecting \( \sigma_{imp} \) for the C-Mn steel category (i.e., for CE: 0.38–0.48) was found to be HV10MAX; while the dominating factor affecting \( \sigma_{imp} \) was H for the HSLA steels category (i.e., for CE: 0.38–0.48); this can be attributed to relatively high percentages of the alloying elements that exist in HSLA steels, such as V, Ni, Cr, and Mo. The dominating welding factor affecting HV10MAX was found to be \( t_{800/500} \) for both C-Mn steels and HSLA steels.

Mechanistic models, linear and logarithmic, were used to develop simplified models that successfully simulated both \( \sigma_{imp} \) and HV10MAX. The \( \sigma_{imp} \) model was developed as a function of HV10MAX and diffusible hydrogen content (H), while the HV10MAX model was developed as a function of the cooling time between 800° and 500°C \( (t_{800/500}) \) and the base metal carbon equivalent (CE). For C-Mn (CE: 0.38–0.48) or HSLA (CE: 0.52–0.69), the results from the developed models have a good match with the experimental results for both \( \sigma_{imp} \) and HV10MAX; furthermore,
the same developed models successfully simulated \(\sigma_{\text{imp}}\) and HV10MAX for the whole range of CE, including the two steel categories together (i.e., with CE range between 0.38 and 0.69). The developed models provide the designer with a reliable simplified engineering tool by which the designer can evaluate the maximum HAZ hardness (HV10MAX) and the implant static tensile limit stress (\(\sigma_{\text{imp}}\)) in steel weldments.

References


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<th>Parameter</th>
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