HEAT FLOW DURING WELDING

- ONE-DIMENSIONAL PLANAR SOLUTION

\[ T - T_0 = \frac{Q/A}{(4\pi t)^{1/2}} \cdot \frac{1}{\rho c_p} \cdot \exp \left[ -\frac{x^2}{4at} \right] \]

Example: Friction weld

\( t_0 < t_1 < t_2 \)

- TWO-DIMENSIONAL LINE SOURCE SOLUTION

\[ T - T_0 = \frac{Q/\delta}{(4\pi t)^{1/2}} \cdot \frac{1}{\rho c_p} \cdot \exp \left[ -\frac{r^2}{4at} \right] \]

\[ r = \sqrt{x^2 + y^2} \]

Example: Two-dimensional Gaussian

Deep penetration laser or electron beam
**Three-Dimensional Heat Flow - Point Source Solution**

\[
T - T_0 = \frac{Q}{(4\pi at)^{3/2}} \cdot \frac{1}{\rho C_p} \exp\left(-\frac{R^2}{4\pi at}\right)
\]

\( R = \sqrt{x^2+y^2+z^2} \)

\( Q \) is the strength of a "buried" heat source.

If the heat source is on the top surface of a thick plate, \( Q'(\text{top surface}) = \frac{Q}{2} \)

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**Rosenthal Moving Point Source Solution**

\[
T - T_0 = \frac{8}{2\pi \lambda \rho} \cdot \frac{1}{R} \exp\left[-\frac{\nu}{2\lambda} (R+\lambda)\right]
\]

Moving in \( x \)-direction, at velocity, \( \nu \).

\( \rho \) is the strength of a point heat source on the surface.

In dimensionless form \( \Theta = \frac{1}{\rho} \exp(-\rho + \lambda) \)
<table>
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<th>Criterion</th>
<th>Formula (wt %)</th>
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<td>Carbon equivalent</td>
<td></td>
<td>[ C_{equiv} = C + \frac{Mn}{6} + \frac{Cr + Mn + V}{5} + \frac{Ni + Cu}{15} ]</td>
</tr>
<tr>
<td>Carbon equivalent for the pearlite-free and reduced-pearlite steels</td>
<td></td>
<td>[ C^D_{equiv} = C + \frac{Si}{25} + \frac{Mn + Cr}{16} + \frac{Cr}{20} + \frac{Ni}{20} + \frac{Mo}{20} + \frac{V}{15} ]</td>
</tr>
<tr>
<td>Maximum hardness of the underbead zone</td>
<td></td>
<td>[ HV_{max} = 90 + 1050 C + 47 Si + 75 Mn + 30 Ni + 31 Cr ]</td>
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<tr>
<td>Cracking parameter for low-alloy steels</td>
<td></td>
<td>[ P_{CM} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{15} ]</td>
</tr>
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</table>
| Cracking parameter for the low-alloy steels. Cold cracks | The cracks can occur when \( P_{WB} > 0 \) | \[ P_{WB} = P_{CM} + \frac{H}{60} + \frac{K}{40 \times 10^5} \]  
\( H \)-glycerine test, \( H = 0.64 H_{IW} - 0.93 \)  
For butt joints, \( K = 66 s \)  
(s = sheet thickness, mm) |
| Cracking parameter for cold cracks | The cracks occur when \( P_s > 1 \), the cracks do not occur when \( P_s < 0.5 \) | \[ P_s = \log \frac{V_i}{V_1} + \frac{H}{10} + \frac{K}{5000} \]  
\( V_i \) is the actual cooling rate of the HAZ at 300°C  
\( V_1 \) is the critical rate for martensitic reaction  
\( H \) is the amount of diffusible hydrogen in the base metal (IIW)  
\( K \) is the intensity of restraint for the butt joints \( K = 66a \) |
| Cracking parameter for cold cracks | The cracks do not occur when \( P_{NB} < 0.25 \% \) | \[ P_{NB} = C + \frac{Si}{20} + \frac{Mn}{10} + \frac{Cu}{20} + \frac{Cr}{30} + \frac{Mo}{20} \] |
| Calculation of preheat temperature | | \[ T = 1.440 P_{WB} - 392 \degree C \]  
\[ T = 350 \left( \frac{1}{360} [360 C + 40 (Mn + Cr)] + 20 Ni + 28 Mo \right) \times \left[ 1 + 0.005 s - 0.25s \right]^{0.66} \degree C \]  
\( s \) = sheet thickness in mm |
| Hot cracking susceptibility (HCS) | Cracks do not occur when HCS < 4, but for the low-alloy steels HCS = 1.6 + 2 | \[ \text{HCS} = \frac{C(S + P) + \frac{Si}{25} + \frac{Ni}{100}}{3Mn + Cr + Mo + V} \times 10^6 \] |
| Susceptibility of steel to stress-relief cracking | \( P_{SR} \leq 0 \) | \[ P_{SR} = Cr + Cu + 2 Mo + 7 Nb - 5 Ti - 2 \] |