STEEL 212. 0.3 % C Cr Ni Mo  LOW ALLOY STEEL

Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2534</td>
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<td></td>
</tr>
</tbody>
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Composition (wt-%)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,29</td>
<td>0,22</td>
<td>0,52</td>
<td>0,009</td>
<td>0,010</td>
<td>1,02</td>
<td>3,2</td>
<td>0,25</td>
<td>0,05</td>
<td>0,03</td>
<td>0,010</td>
<td>0,005</td>
</tr>
</tbody>
</table>

Thermal Analysis

Average Cooling Rate, $R$, ($^\circ$/s)

<table>
<thead>
<tr>
<th>$R$ (°C/s)</th>
<th>2,0</th>
<th>0,5</th>
<th>0,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquidus temperature, austenitic primary phase, °C</td>
<td>1486</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Liquidus temperature, ferritic primary phase, °C</td>
<td>-</td>
<td>1487</td>
<td>1486</td>
</tr>
<tr>
<td>Temperature of austenite formation, °C</td>
<td>-</td>
<td>1478</td>
<td>1477</td>
</tr>
<tr>
<td>Solidus temperature, °C</td>
<td>1415</td>
<td>1425</td>
<td>1435</td>
</tr>
<tr>
<td>Solidification range, °C</td>
<td>70</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Solidification time, s</td>
<td>80</td>
<td>220</td>
<td>650</td>
</tr>
</tbody>
</table>

Precipitates

- 

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1,7</td>
<td>1,4</td>
<td>2,2</td>
</tr>
</tbody>
</table>

$R = 0,5$ °C/s

$T_q = 1360$ °C
Partly solidified

Figure 1
\( R = 0.5 \degree \text{C/s} \)
\( T_q = 1480 \degree \text{C} \)
\( d = 70 \mu \text{m} \)
\( \delta \)-dendrites and quenched liquid (L).

400 \( \mu \text{m} \times 25 \)

Completely solidified

Figure 2
\( R = 2.0 \degree \text{C/s} \)
\( T_q = 1360 \degree \text{C} \)
\( d = 75 \mu \text{m} \)
\( \gamma \)-dendrites.
(Note: primary \( \gamma \) at this cooling rate.)

400 \( \mu \text{m} \times 25 \)

Figure 3
\( R = 0.5 \degree \text{C/s} \)
\( T_q = 1360 \degree \text{C} \)
\( d = 110 \mu \text{m} \)
Figures 3–4: Former \( \delta \)-dendrites, transformed to \( \gamma \) by the peritectic reaction.

400 \( \mu \text{m} \times 25 \)

Figure 4
\( R = 0.1 \degree \text{C/s} \)
\( T_q = 1360 \degree \text{C} \)
\( d = 180 \mu \text{m} \)

400 \( \mu \text{m} \times 25 \)
STEEL 213. 0,35% C Cr Mo LOW ALLOY STEEL

Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2234</td>
<td>4135</td>
<td>1.7220</td>
</tr>
</tbody>
</table>

Composition (wt-%)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>Al (wt%)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.35</td>
<td>0.24</td>
<td>0.67</td>
<td>0.010</td>
<td>0.020</td>
<td>0.92</td>
<td>0.05</td>
<td>0.19</td>
<td>0.07</td>
<td>0.02</td>
<td>0.004</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Thermal Analysis

Liquidus temperature, ferritic primary phase, °C

<table>
<thead>
<tr>
<th>Average Cooling Rate, R, °C/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,0</td>
</tr>
<tr>
<td>1494</td>
</tr>
<tr>
<td>1479</td>
</tr>
<tr>
<td>1405</td>
</tr>
</tbody>
</table>

Temperature of austenite formation, °C

Solidus temperature, °C

Solidification range, °C

Solidification time, s

Precipitates

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>

R = 0.5 °C/s

Tq = 1340 °C
Partly solidified

Figure 1
$R = 0.5^\circ\text{C/s}$
$T_q = 1485^\circ\text{C}$
$d = 65 \mu\text{m}$
$\delta$-dendrites and quenched liquid (L).

$400 \mu\text{m} \times 25$

Completely solidified

Figure 2
$R = 2.0^\circ\text{C/s}$
$T_q = 1340^\circ\text{C}$
$d = 80 \mu\text{m}$
Figures 2–4: Former $\delta$-dendrites, transformed to $\gamma$ by the peritectic reaction.

$400 \mu\text{m} \times 25$

Figure 3
$R = 0.5^\circ\text{C/s}$
$T_q = 1340^\circ\text{C}$
$d = 100 \mu\text{m}$

$400 \mu\text{m} \times 25$

Figure 4
$R = 0.1^\circ\text{C/s}$
$T_q = 1340^\circ\text{C}$
$d = 190 \mu\text{m}$

$400 \mu\text{m} \times 25$
STEEL 214. 0.5% C Cr LOW ALLOY STEEL

Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
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<tbody>
<tr>
<td>2230</td>
<td>6150</td>
<td>1.8159</td>
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Composition (wt-%)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.52</td>
<td>0.22</td>
<td>0.85</td>
<td>0.010</td>
<td>0.006</td>
<td>1.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.04</td>
<td>0.14</td>
<td>\leq 0.004</td>
<td>0.008</td>
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</table>

Thermal Analysis

Average Cooling Rate, \( R \) (°C/s)

<table>
<thead>
<tr>
<th>Element</th>
<th>2.0</th>
<th>0.5</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquidus temperature, austenitic primary phase, °C</td>
<td>1482</td>
<td>1482</td>
<td>1483</td>
</tr>
<tr>
<td>Solidus temperature, °C</td>
<td>1380</td>
<td>1385</td>
<td>1400</td>
</tr>
<tr>
<td>Solidification range, °C</td>
<td>100</td>
<td>95</td>
<td>80</td>
</tr>
<tr>
<td>Solidification time, s</td>
<td>85</td>
<td>250</td>
<td>740</td>
</tr>
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</table>

Precipitates

Small amount of interdendritic carbides.

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

\[ R = 0.5 \text{ °C/s} \]

\[ Tq = 1310 \text{ °C} \]
Partly solidified

Figure 1
R = 0.5°C/s
Tq = 1470°C
d = 55 μm
γ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

Figure 2
R = 2.0°C/s
Tq = 1310°C
d = 75 μm
Figures 2–4: γ-dendrites.

400 μm × 25

Figure 3
R = 0.5°C/s
Tq = 1310°C
d = 90 μm

400 μm × 25

Figure 4
R = 0.1°C/s
Tq = 1310°C
d = 140 μm

400 μm × 25
STEEL 215. 0.55% C Cr Ni Mo LOW ALLOY STEEL

Designations

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<td>1.2721</td>
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</table>

Composition (wt-%)

<table>
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<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>A&lt;sub&gt;tot&lt;/sub&gt;</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>0.27</td>
<td>0.50</td>
<td>0.019</td>
<td>0.012</td>
<td>0.99</td>
<td>3.0</td>
<td>0.31</td>
<td>0.06</td>
<td>0.08</td>
<td>0.011</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Thermal Analysis

![Thermal Analysis Diagram]

Liquidus temperature, austenitic primary phase, °C
Temperature of formation of eutectic, °C
Solidus temperature, °C
Solidification range, °C
Solidification time, s

<table>
<thead>
<tr>
<th>Average Cooling Rate, R, (°C/s)</th>
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<td>2.0</td>
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<tr>
<td>1471</td>
</tr>
<tr>
<td>1365 - 1335</td>
</tr>
<tr>
<td>1335</td>
</tr>
<tr>
<td>140</td>
</tr>
<tr>
<td>100</td>
</tr>
</tbody>
</table>

Precipitates

Interdendritic carbide-austenite eutectic, Fe<sub>3</sub>P and MnS, (see figure 5).

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.1</td>
<td>1.2</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>R = 0.5 °C/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T&lt;sub&gt;q&lt;/sub&gt; = 1290 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Partly solidified

Figure 1
\[ R = 0.5^\circ \text{C/s} \]
\[ T_q = 1465 \, ^\circ \text{C} \]
\[ d = 65 \, \mu \text{m} \]
\( \gamma \)-dendrites and quenched liquid (L).

400 \( \mu \)m \( \times \) 25

Completely solidified

Figure 2
\[ R = 2.0^\circ \text{C/s} \]
\[ T_q = 1290 \, ^\circ \text{C} \]
\[ d = 70 \, \mu \text{m} \]
Figures 2–4: \( \gamma \)-dendrites.

400 \( \mu \)m \( \times \) 25

Figure 3
\[ R = 0.5^\circ \text{C/s} \]
\[ T_q = 1290 \, ^\circ \text{C} \]
\[ d = 90 \, \mu \text{m} \]

400 \( \mu \)m \( \times \) 25

Figure 4
\[ R = 0.1^\circ \text{C/s} \]
\[ T_q = 1290 \, ^\circ \text{C} \]
\[ d = 130 \, \mu \text{m} \]

400 \( \mu \)m \( \times \) 25
Figure 5

\[ R = 0.5^\circ C/s \]
\[ T_q = 1290^\circ C \]

Interdendritic area with carbide-austenite eutectic (E), Fe\(_3\)P and MnS.

\[ \times 1000 \quad 10 \mu m \]
STEEL 216. 1.0% C Cr  LOW ALLOY STEEL

Designations

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<tr>
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<th>AISI</th>
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<td>52100</td>
<td>1.3505</td>
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Composition (wt-%)

<table>
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<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.01</td>
<td>0.23</td>
<td>0.33</td>
<td>0.021</td>
<td>0.026</td>
<td>1.55</td>
<td>0.02</td>
<td>0.01</td>
<td>0.04</td>
<td>0.04</td>
<td>0.011</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Thermal Analysis

![Graph showing thermal analysis with labeled points and temperature ranges.

Average Cooling Rate, R, (°C/s)

<table>
<thead>
<tr>
<th>Average Cooling Rate, R, (°C/s)</th>
<th>2.0</th>
<th>0.5</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquidus temperature, austenitic primary phase, °C</td>
<td>1450</td>
<td>1450</td>
<td>1451</td>
</tr>
<tr>
<td>Temperature of formation of eutectic, °C</td>
<td>1320 - 1270</td>
<td>1340 - 1300</td>
<td>~1300</td>
</tr>
<tr>
<td>Solidus temperature, °C</td>
<td>1270</td>
<td>1300</td>
<td>~1300</td>
</tr>
<tr>
<td>Solidification range, °C</td>
<td>180</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Solidification time, s</td>
<td>170</td>
<td>330</td>
<td>1400</td>
</tr>
</tbody>
</table>

Precipitates

1. Interdendritic Fe_{3}P-carbide-austenite eutectic (14% Cr, 5% P). The eutectic remained after cooling to 850 °C (see figures 5 and 6), but was dissolved after homogenizing for 4 h at 1200 °C.
2. Interdendritic MnS.

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.6</td>
</tr>
</tbody>
</table>

R = 0.5 °C/s

R_{t} = 1250 °C
Partly solidified

Figure 1
R = 0.5°C/s
Tq = 1440°C
d = 60 μm
γ-dendrites and quenched liquid (L).

× 25 400 μm

Completely solidified

Figure 2
R = 2.0°C/s
Tq = 1250°C
d = 75 μm
Figures 2–4: γ-dendrites.

× 25 400 μm

Figure 3
R = 0.5°C/s
Tq = 1250°C
d = 90 μm

× 25 400 μm

Figure 4
R = 0.1°C/s
Tq = 1250°C
d = 140 μm

× 25 400 μm
Interdendritic Fe₃P-carbide-austenite eutectic (E) (approximately 0.1 vol-%). The eutectic contains 14% Cr and 5% P.

After cooling to 850°C, small amounts of the eutectic shown in figure 5 remained. (Annealing for 4 h at 1200°C completely eliminated the eutectic.)
3. Chromium Steels

Steels with chromium as the only, or the dominant alloying element are normally called chromium steels. The two common groups included here are steels with 5 and 13% chromium. In the first family the alloying addition is used to increase hardenability and to give the final product a favourable combination of strength and toughness.

In the 13% Cr-steels, chromium imparts both corrosion resistance and strength. With reference to the structure of the steel products, the group comprises ferritic stainless (C < 0.08%), hardenable martensitic stainless (C ≥ 0.09%), and low carbon hardenable martensitic steels with 4–6% nickel. Because of their constitutional similarity at high temperatures, the 5 and 13% chromium steels are kept together in this work, rather than grouping the 13% Cr-steels with the Cr-Ni stainless materials.

Steels containing 17–25% chromium have not been examined. They are similar to the 13% Cr-group in regard to solidification and structure at high temperatures.

Chromium steels are produced as castings and ingots of moderate size, continuous casting is unusual. Both the groups of steels investigated are made with a wide range of carbon contents. For a given chromium level the solidification mode is strongly dependent on carbon; this can be seen in the pseudobinary phase diagrams, figures 3.1 and 3.2. Account was taken of this effect of carbon when choosing the production steels for examination; these are given in tables 3.1 and 3.2:

![Figure 3.2 Fe-13Cr-C system](Figures 3.1 and 3.2 after Bungardt et al. Arch. Eisenhüttenw. 29 (1958) 3, 193–203, Kc = Fe3C, K1 = M23C6, K2 = M7C3)

<table>
<thead>
<tr>
<th>No.</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>0.13</td>
<td>0.4</td>
<td>0.4</td>
<td>5.0</td>
<td>—</td>
<td>0.6</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>302</td>
<td>0.35</td>
<td>1.0</td>
<td>0.5</td>
<td>5.2</td>
<td>0.2</td>
<td>1.3</td>
<td>1.0</td>
<td>—</td>
</tr>
<tr>
<td>303</td>
<td>0.50</td>
<td>1.0</td>
<td>0.5</td>
<td>5.1</td>
<td>0.2</td>
<td>1.4</td>
<td>1.2</td>
<td>—</td>
</tr>
<tr>
<td>304</td>
<td>0.96</td>
<td>0.3</td>
<td>0.7</td>
<td>5.2</td>
<td>0.1</td>
<td>1.2</td>
<td>0.2</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3.1 5% chromium steels

<table>
<thead>
<tr>
<th>No.</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>305</td>
<td>0.04</td>
<td>0.5</td>
<td>0.6</td>
<td>13.4</td>
<td>5.5</td>
<td>—</td>
</tr>
<tr>
<td>306</td>
<td>0.07</td>
<td>0.5</td>
<td>0.5</td>
<td>12.9</td>
<td>0.2</td>
<td>—</td>
</tr>
<tr>
<td>307</td>
<td>0.14</td>
<td>0.2</td>
<td>0.7</td>
<td>12.0</td>
<td>1.2</td>
<td>—</td>
</tr>
<tr>
<td>308</td>
<td>0.32</td>
<td>0.2</td>
<td>0.3</td>
<td>13.9</td>
<td>0.2</td>
<td>—</td>
</tr>
<tr>
<td>309</td>
<td>0.69</td>
<td>0.4</td>
<td>0.6</td>
<td>13.1</td>
<td>0.2</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3.2 13% chromium steels (see also table 4.1)

As indicated in figures 3.1 and 3.2 these grades cover the following solidification processes:

- primary ferrite formation
- primary ferrite formation followed by a peritectic reaction
- primary austenite formation

It should be noted that the pseudobinary phase diagrams are strictly valid for ternary Fe-Cr-C-alloys only. The superimposed lines for the commercial steel grades are therefore only indicative.

![Figure 3.1 Fe-5Cr-C system](Figures 3.1 and 3.2 after Bungardt et al. Arch. Eisenhüttenw. 29 (1958) 3, 193–203, Kc = Fe3C, K1 = M23C6, K2 = M7C3)

References

The solidification of chromium steels has not been widely studied. General aspects of the process have been reported. [55–59]. Research work on microsegregation is described in references [60–64].
STEEL 301. 0.1% C 5% CHROMIUM STEEL

Designations

<table>
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<tr>
<td></td>
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Composition (wt-%)

<table>
<thead>
<tr>
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<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.13</td>
<td>0.36</td>
<td>0.37</td>
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<td>0.007</td>
<td>5.0</td>
<td>0.01</td>
<td>0.58</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.009</td>
<td>0.006</td>
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Thermal Analysis

Average Cooling Rate, $R$, °C/s

<table>
<thead>
<tr>
<th></th>
<th>2.0</th>
<th>0.5</th>
<th>0.1</th>
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<tr>
<td></td>
<td>1508</td>
<td>1501</td>
<td>1506</td>
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<td></td>
<td>1443</td>
<td>1426</td>
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<tr>
<td></td>
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<td>1415</td>
<td>1440</td>
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<tr>
<td></td>
<td>105</td>
<td>85</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td>190</td>
<td>790</td>
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</table>

Liquidus temperature, ferritic primary phase, °C

Temperature of austenite formation, °C

Solidus temperature, °C

Solidification range, °C

Solidification time, s

Precipitates

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

$R = 0.5$ °C/s

$T_q = 1375$ °C
Partly solidified

Figure 1
R = 0.5°C/s  
Tq = 1495°C  
d = 65 µm  
δ-dendrites and quenched liquid (L).

× 25  400 µm

Completely solidified

Figure 2
R = 2.0°C/s  
Tq = 1375°C  
d = 85 µm  
Figures 2–4: Former δ-dendrites, transformed to γ by the peritectic reaction.

× 25  400 µm

Figure 3
R = 0.5°C/s  
Tq = 1375°C  
d = 160 µm

× 25  400 µm

Figure 4
R = 0.1°C/s  
Tq = 1375°C  
d = 275 µm

× 25  400 µm
STEEL 302. 0.35% C Mo V 5% CHROMIUM STEEL

Designations

<table>
<thead>
<tr>
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<th>Werkstoff Nr</th>
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Composition (wt-%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
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<tbody>
<tr>
<td>0.35</td>
<td>1.03</td>
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<td>0.020</td>
<td>0.007</td>
<td>5.2</td>
<td>0.23</td>
<td>1.34</td>
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<td>1.0</td>
<td>0.013</td>
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</table>

Thermal Analysis

![Diagram of thermal analysis with annotations]

<table>
<thead>
<tr>
<th>R (°C/s)</th>
<th>2.0</th>
<th>0.5</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>1471</td>
<td>1464</td>
<td>1470</td>
</tr>
<tr>
<td>1471</td>
<td>1370</td>
<td>1387</td>
<td>1412</td>
</tr>
<tr>
<td>1370</td>
<td>1335</td>
<td>1360</td>
<td>1380</td>
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<tr>
<td>135</td>
<td>135</td>
<td>105</td>
<td>90</td>
</tr>
<tr>
<td>100</td>
<td>250</td>
<td>990</td>
<td></td>
</tr>
</tbody>
</table>

| Liquidus temperature, ferritic primary phase, °C | 1 |
| Temperature of austenite formation, °C | 2 |
| Solidus temperature, °C | 3 |
| Solidification range, °C |     |
| Solidification time, s |     |

Precipitates

Small amount of eutectic carbide.

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>1.2</td>
<td>1.0</td>
<td>1.5</td>
<td>1.7</td>
</tr>
</tbody>
</table>

R = 0.5 °C/s

Tq = 1300 °C
Partly solidified

Figure 1
R = 0.5°C/s  
Tq = 1450°C  
d = 55 μm  
δ-dendrites and quenched liquid (L).

× 25  400 μm

Completely solidified

Figure 2
R = 2.0°C/s  
Tq = 1300°C  
d = 70 μm  
Figures 2–4: Former δ-dendrites, transformed to γ by the peritectic reaction.

× 25  400 μm

Figure 3
R = 0.5°C/s  
Tq = 1300°C  
d = 80 μm

× 25  400 μm

Figure 4
R = 0.1°C/s  
Tq = 1300°C  
d = 120 μm

× 25  400 μm
**STEEL 303. 0,5 % C Mo V 5 % CHROMIUM STEEL**

### Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tbody>
</table>

### Composition (wt-%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al</th>
<th>N</th>
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</thead>
<tbody>
<tr>
<td>0.50</td>
<td>1.00</td>
<td>0.48</td>
<td>0.025</td>
<td>0.010</td>
<td>5.1</td>
<td>0.18</td>
<td>1.36</td>
<td>0.10</td>
<td>0.02</td>
<td>1.20</td>
<td>0.013</td>
<td>0.036</td>
</tr>
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### Thermal Analysis

#### Thermal Analysis Diagram

- Liquidus temperature, ferritic primary phase, °C
- Temperature of austenite formation, °C
- Temperature of formation of MC-austenite eutectic, °C
- Solidus temperature, °C
- Solidification range, °C
- Solidification time, s

<table>
<thead>
<tr>
<th>Average Cooling Rate, R, (°C/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>0.1</td>
</tr>
</tbody>
</table>

#### Precipitates

1. Interdendritic MC-austenite eutectic, MC was of the VC type, (see figures 6 – 8).
2. Small amount of interdendritic M₂₃C₆-austenite eutectic, (M was Cr, Fe and Mo), precipitated after the MC carbide.

### Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3</td>
<td>1.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

| R = 0.5 °C/s | Tq = 1200 °C |
Partly solidified

Figure 1
R = 0.5°C/s
Tq = 1445°C
d = 55 μm
δ-dendrites and quenched liquid (L).

\[ \times 25 \quad 400 \, \mu m \]

Completely solidified

Figure 2
R = 2.0°C/s
Tq = 1140°C
d = 60 μm
Figures 2–4: Former δ-dendrites, (transformed to γ by the peritectic reaction), and interdendritic carbide eutectic.

\[ \times 25 \quad 400 \, \mu m \]

Figure 3
R = 0.5°C/s
Tq = 1200°C
d = 80 μm

\[ \times 25 \quad 400 \, \mu m \]

Figure 4
R = 0.1°C/s
Tq = 1200°C
d = 110 μm

\[ \times 25 \quad 400 \, \mu m \]
Figure 5
R = 2.0°C/s
Tq = 1290°C
Quenched liquid.

10 μm × 1000

Figure 6
R = 2.0°C/s
Tq = 1200°C
Eutectic formation of MC.
(L→MC + γ)

10 μm × 1000

Figure 7
R = 2.0°C/s
Tq = 1000°C
Morphology of MC.

10 μm × 1000

Figure 8
R = 2.0°C/s
Tq = 1000°C
Interdendritic distribution of MC.

100 μm × 150
STEEL 304. 1,0 % C Mo 5 % CHROMIUM STEEL

Designations

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Composition (wt-%)

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<tr>
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<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
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<tr>
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<td>0,29</td>
<td>0,67</td>
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<td>0,015</td>
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<td>0,21</td>
<td>0,014</td>
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Thermal Analysis

<table>
<thead>
<tr>
<th></th>
<th>Liquidus temperature, austenitic primary phase, °C</th>
<th>Temperature of formation of eutectic, °C</th>
<th>Solidus temperature, °C</th>
<th>Solidification range, °C</th>
<th>Solidification time, s</th>
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<tbody>
<tr>
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<td>1150 – 1130</td>
<td>1130</td>
<td>305</td>
<td>185</td>
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<tr>
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<td>1434</td>
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<td>1200</td>
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<td>1215</td>
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<td>2700</td>
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Precipitates

Interdendritic M₇C₃ – austenite eutectic, (see figures 5 – 7).

Microsegregation

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,4</td>
<td>1,9</td>
<td>1,7</td>
</tr>
</tbody>
</table>

\[ R = 0,5 \degree C/s \]

\[ T_q = 1200 \degree C \]
Partly solidified

Figure 1
R = 0.5 C/s
Tq = 1420°C
d = 55 μm
γ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

Figure 2
R = 2.0 C/s
Tq = 1130°C
d = 65 μm
Figures 2—4: γ-dendrites and interdendritic carbide eutectic.

400 μm × 25

Figure 3
R = 0.5°C/s
Tq = 1200°C
d = 80 μm

400 μm × 25

Figure 4
R = 0.1°C/s
Tq = 1200°C
d = 110 μm

400 μm × 25
Figure 5

R = 2.0°C/s
Tq = 1200°C
Quenched liquid.

× 1000 10 μm

Figure 6

R = 2.0°C/s
Tq = 1000°C
Morphology of M₇C₃.

× 1000 10 μm

Figure 7

R = 2.0°C/s
Tq = 1000°C
Interdendritic distribution of M₇C₃.

× 150 100 μm
STEEL 305. 0.04% C 5% Ni 13% CHROMIUM STEEL

Designations

<table>
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<tr>
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Composition (wt-%)

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<tr>
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<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
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<tbody>
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<td>0.04</td>
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<td>0.010</td>
<td>0.009</td>
<td>13.4</td>
<td>5.5</td>
<td>0.07</td>
<td>0.07</td>
<td>0.01</td>
<td>0.019</td>
<td>0.032</td>
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Thermal Analysis

![Thermal Analysis Diagram]

Average Cooling Rate, $R$, (°C/s)

<table>
<thead>
<tr>
<th></th>
<th>2.0</th>
<th>0.5</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>0.5°C/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{q}$</td>
<td>1350°C</td>
<td>1350°C</td>
<td>1350°C</td>
</tr>
<tr>
<td>Solidus temperature, °C</td>
<td>115</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Solidification range, °C</td>
<td>100</td>
<td>230</td>
<td>670</td>
</tr>
<tr>
<td>Liquidus temperature, ferritic primary phase, °C</td>
<td>1470</td>
<td>1476</td>
<td>1476</td>
</tr>
<tr>
<td>Temperature of austenite formation, °C</td>
<td>1410</td>
<td>1419</td>
<td>1425</td>
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</table>

Precipitates

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
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<td>1.2</td>
</tr>
<tr>
<td>$R$</td>
<td>0.5°C/s</td>
<td></td>
</tr>
<tr>
<td>$T_{q}$</td>
<td>1350°C</td>
<td></td>
</tr>
</tbody>
</table>

R = 0.5°C/s

$T_{q}$ = 1350°C
Partly solidified

Figure 1
\[ R = 0.5^\circ \text{C/s} \]
\[ Tq = 1473^\circ \text{C} \]
\[ d = 75 \mu \text{m} \]
\( \delta \)-dendrites and quenched liquid (L).

\[ \times 25 \quad 400 \mu \text{m} \]

Completely solidified

Figure 2
\[ R = 2.0^\circ \text{C/s} \]
\[ Tq = 1350^\circ \text{C} \]
\[ d = 140 \mu \text{m} \]
Figures 2–4: Former \( \delta \)-dendrites (D).
White interdendritic areas (ID).
Most of the \( \delta \) transformed to \( \gamma \) by the peritectic reaction.

\[ \times 25 \quad 400 \mu \text{m} \]

Figure 3
\[ R = 0.5^\circ \text{C/s} \]
\[ Tq = 1350^\circ \text{C} \]
\[ d = 240 \mu \text{m} \]

\[ \times 25 \quad 400 \mu \text{m} \]

Figure 4
\[ R = 0.1^\circ \text{C/s} \]
\[ Tq = 1350^\circ \text{C} \]
\[ d = 520 \mu \text{m} \]

\[ \times 25 \quad 400 \mu \text{m} \]
Figure 5
R = 0.5°C/s  
Tq = 1200°C  
(d_{200} = 260 \mu m)  
Former δ-dendrites (D).  
White interdendritic areas (ID).  
Most of the δ transformed to γ by the peritectic reaction.

400 \mu m \times 25

Figure 6
R = 2.0°C/s  
Tq = 1350°C  
Residual dendritic ferrite (δ)  
in the γ-matrix.

25 \mu m \times 600

Figure 7
R = 0.1°C/s  
Tq = 1350°C  
Residual dendritic ferrite (δ)  
in the γ-matrix.

25 \mu m \times 600
STEEL 306. 0,07 % C 13 % CHROMIUM STEEL

Designations

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<th>Werkstoff Nr</th>
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<tbody>
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Composition (wt-%)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,07</td>
<td>0,54</td>
<td>0,48</td>
<td>0,020</td>
<td>0,006</td>
<td>12,9</td>
<td>0,17</td>
<td>0,02</td>
<td>0,10</td>
<td>0,01</td>
<td>\leq 0,01</td>
<td>0,026</td>
<td>0,039</td>
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</table>

Thermal Analysis

![Thermal Analysis Graph]

Average Cooling Rate, R, (°C/s)

<table>
<thead>
<tr>
<th>Rate</th>
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<th>0,5</th>
<th>0,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1497</td>
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<td>1500</td>
<td></td>
</tr>
<tr>
<td>1435</td>
<td>1440</td>
<td>1455</td>
<td></td>
</tr>
</tbody>
</table>

Liquidus temperature, ferritic primary phase, °C 1
Solidus temperature, °C 2
Temperature of solid phase transformation of ferrite to austenite, °C 3
Solidification range, °C
Solidification time, s

Precipitates

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1,0</td>
<td>1,0</td>
</tr>
</tbody>
</table>

R = 0,5 °C/s

T_q = 1400 °C
Partly solidified

Figure 1
\[ R = 0.5^\circ C/s \]
\[ T_q = 1498^\circ C \]
\[ d = 90 \mu m \]
\( \delta \)-dendrites and quenched liquid (L).

400 \( \mu m \) × 25

Completely solidified

Figure 2
\[ R = 2.0^\circ C/s \]
\[ T_q = 1400^\circ C \]
\[ d = 205 \mu m \]
Figures 2–3: \( \delta \)-dendrites.
Light interdendritic areas.
(Interference contrast.)

400 \( \mu m \) × 25

Figure 3
\[ R = 0.5^\circ C/s \]
\[ T_q = 1400^\circ C \]
\[ d = 260 \mu m \]

400 \( \mu m \) × 25

Figure 4
\[ R = 0.1^\circ C/s \]
\[ T_q = 1400^\circ C \]
\[ d = - \]

No dendrites visible due to absence of segregation. Austenite (dark) precipitated during quenching.

400 \( \mu m \) × 25
Figure 5
R = 0.5°C/s
Tq = 1400°C
Austenite (dark) precipitated during quenching from 1400°C.

× 25  400 μm

Figure 6
R = 0.5°C/s
Tq = 1200°C
Austenite (γ) precipitated during cooling to 1200°C (solid state transformation). (d_{1200} = 270 μm)

× 25  400 μm
STEEL 307. 0,1 % C  Ni  12 % CHROMIUM STEEL

Designations

<table>
<thead>
<tr>
<th>Designation</th>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
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<tbody>
<tr>
<td></td>
<td>2302(414)</td>
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</table>

Composition (wt-%)

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,14</td>
<td>0,19</td>
<td>0,68</td>
<td>0,009</td>
<td>0,014</td>
<td>12,0</td>
<td>1,20</td>
<td>0,01</td>
<td>0,03</td>
<td>0,01</td>
<td>0,02</td>
<td>0,001</td>
<td>0,040</td>
</tr>
</tbody>
</table>

Thermal Analysis

<table>
<thead>
<tr>
<th>Temperature</th>
<th>dT/dt (°C/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>-1,0</td>
</tr>
<tr>
<td>1300</td>
<td>-1,5</td>
</tr>
<tr>
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<td>0</td>
</tr>
<tr>
<td>1400</td>
<td>+0,5</td>
</tr>
<tr>
<td>1450</td>
<td>+1,0</td>
</tr>
</tbody>
</table>

Average Cooling Rate, R, (°C/s)

<table>
<thead>
<tr>
<th>R (°C/s)</th>
<th>2,0</th>
<th>0,5</th>
<th>0,1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1490</td>
<td>1495</td>
<td>1494</td>
</tr>
<tr>
<td></td>
<td>1416</td>
<td>1425</td>
<td>1401</td>
</tr>
<tr>
<td></td>
<td>1390</td>
<td>1400</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>255</td>
<td>1070</td>
</tr>
</tbody>
</table>

Precipitates

Liquidus temperature, ferritic primary phase, °C: 1
Temperature of austenite formation, °C: 2
Solidus temperature, °C: 3
Solidification range, °C
Solidification time, s

Precipitates

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,1</td>
<td>1,3</td>
</tr>
</tbody>
</table>

R = 0,5 °C/s
Tq = 1360 °C
Partly solidified

Figure 1
\[ R = 0.5^\circ C/s \]
\[ T_q = 1493^\circ C \]
\[ d = 75 \mu m \]
\( \delta \)-dendrites and quenched liquid (L).

\[ \times 25 \quad 400 \mu m \]

Completely solidified

Figure 2
\[ R = 2.0^\circ C/s \]
\[ T_q = 1360^\circ C \]
\[ d = 150 \mu m \]
Figures 2–4: Former \( \delta \)-dendrites (D).
White interdendritic areas (ID).
(Most of the \( \delta \) transformed to \( \gamma \) by the peritectic reaction.)

\[ \times 25 \quad 400 \mu m \]

Figure 3
\[ R = 0.5^\circ C/s \]
\[ T_q = 1360^\circ C \]
\[ d = 180 \mu m \]

\[ \times 25 \quad 400 \mu m \]

Figure 4
\[ R = 0.1^\circ C/s \]
\[ T_q = 1360^\circ C \]
\[ d = 470 \mu m \]

\[ \times 25 \quad 400 \mu m \]
Figure 5
R = 0.5°C/s
Tq = 1200°C
(d_{1200} = 250 \mu m)
Former \(\delta\)-dendrites (D).
White interdendritic areas (ID).
(Most of the \(\delta\) transformed to \(\gamma\) by the peritectic reaction.)

400 \mu m \times 25

Figure 6
R = 2.0°C/s
Tq = 1360°C
Residual dendritic ferrite (\(\delta\)) in the \(\gamma\)-matrix.

25 \mu m \times 600

Figure 7
R = 0.1°C/s
Tq = 1360°C
Residual dendritic ferrite (\(\delta\)) in the \(\gamma\)-matrix.
Figures 6–7: Note the influence of cooling rate on ferrite coarseness.

25 \mu m \times 600
STEEL 308. 0,3 % C 14 % CHROMIUM STEEL

Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2304</td>
<td>(420)</td>
<td>1.4028</td>
</tr>
</tbody>
</table>

Composition (wt-%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,32</td>
<td>0,15</td>
<td>0,30</td>
<td>0,009</td>
<td>0,008</td>
<td>13,9</td>
<td>0,16</td>
<td>0,01</td>
<td>0,01</td>
<td>0,22</td>
<td>0,03</td>
<td>0,003</td>
<td>0,013</td>
</tr>
</tbody>
</table>

Thermal Analysis

Average Cooling Rate, $R$, (°C/s)

<table>
<thead>
<tr>
<th>2,0</th>
<th>0,5</th>
<th>0,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1480</td>
<td>1483</td>
<td>1482</td>
</tr>
<tr>
<td>1400</td>
<td>1407</td>
<td>1401</td>
</tr>
<tr>
<td>1370</td>
<td>1375</td>
<td>1390</td>
</tr>
<tr>
<td>110</td>
<td>105</td>
<td>90</td>
</tr>
<tr>
<td>100</td>
<td>290</td>
<td>1100</td>
</tr>
</tbody>
</table>

Liquidus temperature, ferritic primary phase, °C

Temperature of austenite formation, °C

Solidus temperature, °C

Solidification range, °C

Solidification time, s

Precipitates

Interdendritic ferrite, (see figures 7 – 8).

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1,2</td>
<td>1,0</td>
</tr>
</tbody>
</table>

$R = 0,5$ °C/s

$T_q = 1345$ °C
Partly solidified

Figure 1
R = 0.5°C/s  
Tq = 1410°C  
d = 75 μm  
δ-dendrites (almost completely transformed to γ) and quenched liquid (L), (compare figure 6).

400 μm × 25

Completely solidified

Figure 2
R = 2.0°C/s  
Tq = 1345°C  
d = 75 μm  
Figures 2–4: Former δ-dendrites, (transformed to γ by the peritectic reaction), and interdendritic ferrite (δ).

400 μm × 25

Figure 3
R = 0.5°C/s  
Tq = 1345°C  
d = 100 μm

400 μm × 25

Figure 4
R = 0.1°C/s  
Tq = 1345°C  
d = 210 μm

400 μm × 25
Figure 5
R = 0.5°C/s
Tq = 1200°C
(d_{1200} = 110 \mu m)
Former δ-dendrites, (transformed to γ by the peritectic reaction), and interdendritic ferrite (δ).

\[ R = 2.0°C/s \]
\[ Tq = 1345°C \]
Interdendritic ferrite (δ).

Figure 6
R = 0.5°C/s
Tq = 1410°C
Former δ-dendrite, almost completely transformed to γ by the peritectic reaction, with residual δ in the centre. L = quenched liquid.

\[ R = 0.5°C/s \]
\[ Tq = 1200°C \]
Interdendritic ferrite (δ).
STEEL 309. 0.7 % C 13 % CHROMIUM STEEL

Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Composition (wt-%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>W</th>
<th>V</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,69</td>
<td>0,43</td>
<td>0,64</td>
<td>0,014</td>
<td>0,005</td>
<td>13,1</td>
<td>0,20</td>
<td>0,07</td>
<td>0,02</td>
<td>0,22</td>
<td>0,03</td>
<td>0,002</td>
<td>0,025</td>
</tr>
</tbody>
</table>

Thermal Analysis

Average Cooling Rate, \( R \), (°C/s)

<table>
<thead>
<tr>
<th>2,0</th>
<th>0,5</th>
<th>0,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1442</td>
<td>1448</td>
<td>1444</td>
</tr>
<tr>
<td>1414</td>
<td>1422</td>
<td>1415</td>
</tr>
<tr>
<td>1240–1195</td>
<td>1250–1240</td>
<td>1260–1245</td>
</tr>
<tr>
<td>1195</td>
<td>1240</td>
<td>1245</td>
</tr>
<tr>
<td>245</td>
<td>210</td>
<td>200</td>
</tr>
<tr>
<td>160</td>
<td>405</td>
<td>2140</td>
</tr>
</tbody>
</table>

Precipitates

Interdendritic M₇C₃-austenite eutectic. The amount of carbide eutectic increased with increasing cooling rate, (see figures 5–8).

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1,2</td>
<td>1,0</td>
</tr>
</tbody>
</table>

\( R = 0,5 \) °C/s

\( T_q = 1240 \) °C
Partly solidified

Figure 1
\[ R = 0.5^\circ\text{C/s} \]
\[ T_q = 1418^\circ\text{C} \]
\[ d = 50 \mu\text{m} \]
Former \(\delta\)-dendrites, (completely transformed to \(\gamma\) by the peritectic reaction), and quenched liquid (L).

\[ \times 25 \quad 400 \mu\text{m} \]

Completely solidified

Figure 2
\[ R = 2.0^\circ\text{C/s} \]
\[ T_q = 1195^\circ\text{C} \]
\[ d = 65 \mu\text{m} \]
Figures 2–4: Former \(\delta\)-dendrites, (transformed to \(\gamma\) by the peritectic reaction). Interdendritic carbide eutectic (compare figures 5–8).

\[ \times 25 \quad 400 \mu\text{m} \]

Figure 3
\[ R = 0.5^\circ\text{C/s} \]
\[ T_q = 1240^\circ\text{C} \]
\[ d = 80 \mu\text{m} \]

\[ \times 25 \quad 400 \mu\text{m} \]

Figure 4
\[ R = 0.1^\circ\text{C/s} \]
\[ T_q = 1240^\circ\text{C} \]
\[ d = 130 \mu\text{m} \]

\[ \times 25 \quad 400 \mu\text{m} \]
Figure 5
$R = 0.5^\circ C/s$
$Tq = 1240^\circ C$
Interdendritic M7C3-Y eutectic. 3.5 vol-% carbide.

100 $\mu m \times 150$

Figure 6
$R = 2.0^\circ C/s$
$Tq = 1195^\circ C$
M7C3-Y eutectic. 4.5 vol-% carbide.

25 $\mu m \times 600$

Figure 7
$R = 0.5^\circ C/s$
$Tq = 1245^\circ C$
M7C3-Y eutectic (E) and small amounts of liquid (L).

25 $\mu m \times 600$

Figure 8
$R = 0.1^\circ C/s$
$Tq = 1240^\circ C$
M7C3-Y eutectic. 2.4 vol-% carbide.

25 $\mu m \times 600$
4. Stainless and Heat Resistant Steels

The main alloying element is chromium in amounts between 12 and 30%. Most common stainless steels also contain considerable quantities of other alloying elements of which molybdenum and nickel are the most important. The main object of these additions is to increase the corrosion resistance of the steel and to control the phase composition of the microstructure in the final product. Most commercial stainless and heat resistant steels are found in the following range of standardized compositions, table 4.1:

<table>
<thead>
<tr>
<th>Structure of the steel product</th>
<th>C</th>
<th>Cr</th>
<th>Ni %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferritic</td>
<td>-0.08</td>
<td>12-14</td>
<td></td>
</tr>
<tr>
<td>Martensitic</td>
<td>-0.08</td>
<td>12-14</td>
<td>3-6</td>
</tr>
<tr>
<td>Martensitic</td>
<td>0.09</td>
<td>12-14</td>
<td></td>
</tr>
<tr>
<td>Ferritic-austenitic</td>
<td>-0.10</td>
<td>18-30</td>
<td>4.5-14</td>
</tr>
<tr>
<td>Austenitic</td>
<td>-0.50</td>
<td>16-26</td>
<td>7.35</td>
</tr>
</tbody>
</table>

Table 4.1 Classification of stainless and heat resistant steels

The choice of these alloys was based on the solidification modes indicated by the pseudobinary phase diagrams, such as that shown in figure 4.1.

The types of solidification are:
- primary ferrite formation
- primary ferrite formation followed by a three-phase reaction between liquid, δ and γ
- primary ferrite and austenite formation
- primary austenite formation

In this work the transition δ + liquid → γ is called peritectic reaction as long as the δ-phase is in direct contact with the liquid. When δ is completely surrounded by γ-phase and the reaction rate is governed by solid state diffusion of the alloying elements through γ, the process is denoted peritectic transformation.

The relative amount of austenite usually increases below the solidus temperature, i.e., the remaining ferrite content is dependent on temperature. In alloys with a high carbon content carbides precipitate during solidification.

The structure of the final product should not be confused with the structures present during and immediately after solidification. Many austenitic steels for instance contain considerable quantities of ferrite in their solidification structure.

Other common alloying elements are molybdenum up to 5% and copper up to 3%. Nitrogen, which is usually present at residual levels of about 0.03 - 0.06%, can also be used as an alloying addition of up to 0.2%.

Austenitic steels are produced as castings, ingots of all sizes and as continuously cast billets and slabs. The other types of stainless and heat resistant materials mentioned in table 4.1 are cast predominantly as ingots of a moderate size, although martensitic and ferritic-austenitic steels are also commonly used as castings.

The solidification behaviour is governed by the proportions of austenite- and ferrite-forming elements present. The first group comprises carbon, nitrogen, nickel, manganese, copper and cobalt. (At high concentrations manganese has been reported to be a ferrite former, [66].)

The most important ferrite formers are chromium, silicon, molybdenum, niobium, titanium and aluminium. The ferritic and martensitic grades have already been described in chapter 3. The alloys of the present section, belonging to the ferritic-austenitic and the austenitic groups were chosen to give examples of the different solidification paths. The alloys are listed in table 4.2 in order of increasing tendency to solidify as austenite:

<table>
<thead>
<tr>
<th>No.</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Others %</th>
</tr>
</thead>
<tbody>
<tr>
<td>401</td>
<td>0.04</td>
<td>0.9</td>
<td>0.8</td>
<td>25.1</td>
<td>4.7</td>
<td>1.2</td>
<td></td>
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<tr>
<td>402</td>
<td>0.01</td>
<td>0.3</td>
<td>1.8</td>
<td>19.8</td>
<td>9.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>403</td>
<td>0.02</td>
<td>0.3</td>
<td>0.9</td>
<td>19.5</td>
<td>10.3</td>
<td></td>
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</tr>
<tr>
<td>404</td>
<td>0.04</td>
<td>0.4</td>
<td>1.2</td>
<td>18.4</td>
<td>9.1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>405</td>
<td>0.07</td>
<td>0.6</td>
<td>1.4</td>
<td>17.2</td>
<td>10.3</td>
<td>0.5</td>
<td>Ti 0.5Nb</td>
</tr>
<tr>
<td>406</td>
<td>0.05</td>
<td>0.4</td>
<td>1.7</td>
<td>17.2</td>
<td>12.6</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>407</td>
<td>0.02</td>
<td>0.5</td>
<td>1.6</td>
<td>17.2</td>
<td>13.5</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>408</td>
<td>0.05</td>
<td>0.6</td>
<td>1.7</td>
<td>17.7</td>
<td>13.4</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>409</td>
<td>0.02</td>
<td>0.6</td>
<td>1.8</td>
<td>17.4</td>
<td>12.8</td>
<td>2.8</td>
<td>0.19 N</td>
</tr>
<tr>
<td>410</td>
<td>0.01</td>
<td>0.2</td>
<td>1.8</td>
<td>25.1</td>
<td>22.2</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>411</td>
<td>0.06</td>
<td>1.2</td>
<td>1.8</td>
<td>24.2</td>
<td>20.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>412</td>
<td>0.13</td>
<td>0.5</td>
<td>1.7</td>
<td>24.3</td>
<td>20.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>413</td>
<td>0.01</td>
<td>0.5</td>
<td>1.7</td>
<td>19.2</td>
<td>25.1</td>
<td>4.4</td>
<td>1.5 Cu</td>
</tr>
<tr>
<td>414</td>
<td>0.41</td>
<td>1.0</td>
<td>1.3</td>
<td>25.2</td>
<td>20.6</td>
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<td></td>
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<tr>
<td>415</td>
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<td>0.6</td>
<td>21.1</td>
<td>31.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 Stainless and heat resistant steels

Figure 4.1 Phase diagram Fe-Cr-Ni at 70% Fe. (After Metals Handbook, Vol 8, 1973, 424 - 425)

References

The solidification of stainless and heat resistant alloys has been the subject of many research reports. Papers on general aspects of solidification and phase equilibria include references [65 - 77]. Quantitative discussions of microsegregation have been presented, [68, 69, 71, 73, 77 - 82]. Finally, solidification under welding conditions has also received attention, [72, 79, 83 - 86].
STEEL 401. 0.04 % C 25 % Cr 5 % Ni Mo STAINLESS STEEL

Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2324</td>
<td>(329)</td>
<td>(1.4460)</td>
</tr>
</tbody>
</table>

Composition (wt-%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>Co</th>
<th>Al_{tot}</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.042</td>
<td>0.86</td>
<td>0.76</td>
<td>0.031</td>
<td>0.010</td>
<td>25.1</td>
<td>4.7</td>
<td>1.22</td>
<td>0.08</td>
<td>0.08</td>
<td>≤0.002</td>
<td>0.077</td>
</tr>
</tbody>
</table>

\[
\frac{Cr_{eq}}{Ni_{eq}} = 4.01
\]

Thermal Analysis

Liquidus temperature, ferritic primary phase, °C
Solidus temperature, °C
Solidification range, °C
Solidification time, s
Fraction solidified as ferrite, %

Precipitates

M_{23}C_{6} particles and austenite in grain boundaries and M_{23}C_{6} particles in the matrix, (see figures 5–8). The carbide and austenite were precipitated during quenching from 1360°C.

Microsegregation

<table>
<thead>
<tr>
<th>Element</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.3</td>
<td>1.0</td>
<td>1.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

R = 0.5 °C/s
T_{q} = 1360 °C
Partly solidified

Figure 1
R = 0.5°C/s
Tq = 1468°C
d = 70 μm
δ-dendrites and quenched liquid (L).

Completely solidified

Figure 2
R = 2.0°C/s
Tq = 1360°C
d = 115 μm
Figures 2–4: δ-dendrites. White interdendritic areas (ID). Grain boundaries (G) also visible.

Figure 3
R = 0.5°C/s
Tq = 1360°C
d = 280 μm

Figure 4
R = 0.1°C/s
Tq = 1360°C
d = 550 μm
Figure 5
R = 0.5°C/s
Tq = 1360°C
A = grain boundary with austenite.
B = grain boundary with carbide particles.
C = ferritic matrix with carbide and austenite precipitates.

100 μm × 150

Figure 6
R = 0.5°C/s
Tq = 1360°C
Austenite, formed during quenching, in grain boundary as in fig 5 at A.

10 μm × 1000

Figure 7
R = 0.5°C/s
Tq = 1360°C
Carbide particles (M₂₃C₆), formed during quenching, in a grain boundary as in fig 5 at B. Electron micrograph of thin foil (TEM).

0.5 μm × 30 000

Figure 8
R = 0.5°C/s
Tq = 1360°C
Carbide particles (M₂₃C₆), formed during quenching, in the ferritic matrix as in fig 5 at C. Electron micrograph of thin foil (TEM).

1 μm × 15 000
STEEL 402.  0.01% C  20% Cr 10% Ni  STAINLESS STEEL

Designations

<table>
<thead>
<tr>
<th>SIS</th>
<th>AISI</th>
<th>Werkstoff Nr</th>
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<tbody>
<tr>
<td></td>
<td>308L</td>
<td>1.4316</td>
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Composition (wt-%)

<table>
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<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>Co</th>
<th>Al_{tot}</th>
<th>N</th>
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<tr>
<td></td>
<td>0.012</td>
<td>0.31</td>
<td>1.76</td>
<td>0.008</td>
<td>0.008</td>
<td>19.8</td>
<td>9.9</td>
<td>0.10</td>
<td>0.04</td>
<td>0.02</td>
<td>0.004</td>
<td>0.031</td>
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</tbody>
</table>

$Cr_{eq} = 1.82$
$Ni_{eq} = 1.82$

Thermal Analysis

![Thermal Analysis Graph]

<table>
<thead>
<tr>
<th>Average Cooling Rate, R (°C/s)</th>
<th>2.0</th>
<th>0.5</th>
<th>0.1</th>
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<tbody>
<tr>
<td>Liquidus temperature, ferritic primary phase, °C</td>
<td>1447</td>
<td>1454</td>
<td>1449</td>
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<tr>
<td>Temperature of austenite formation, °C</td>
<td>1366</td>
<td>1391</td>
<td>1405</td>
</tr>
<tr>
<td>Solidus temperature, °C</td>
<td>1325</td>
<td>1360</td>
<td>1390</td>
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<tr>
<td>Solidification range, °C</td>
<td>120</td>
<td>95</td>
<td>60</td>
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<tr>
<td>Solidification time, s</td>
<td>105</td>
<td>255</td>
<td>690</td>
</tr>
<tr>
<td>Fraction solidified as ferrite, %</td>
<td>92</td>
<td>91</td>
<td>97</td>
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</tbody>
</table>

Precipitates

Microsegregation

<table>
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<tr>
<th>Element</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Partly solidified

Figure 1
R = 0.5°C/s  
Tq = 1450°C  
d = 60 μm  
δ-dendrites and quenched liquid (L).

400 μm × 25

Completely solidified

Figure 2
R = 2.0°C/s  
Tq = 1325°C  
d = 150 μm  
Figures 2–4: Former δ-dendrites (D).  
White interdendritic areas (ID).  
(Most of the δ transformed to γ by the peritectic reaction and transformation.)

400 μm × 25

Figure 3
R = 0.5°C/s  
Tq = 1325°C  
d = 270 μm

400 μm × 25

Figure 4
R = 0.1°C/s  
Tq = 1325°C