4. Thermo-mechanical processing of car body steels and aluminium alloys for beverage cans
Iron-cementite phase diagram
## Types of multiphase reactions in metals

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Equation</th>
<th>Phase Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eutectic</td>
<td>$L \rightarrow \alpha + \beta$</td>
<td><img src="image" alt="Eutectic Diagram" /></td>
</tr>
<tr>
<td>Eutectoid</td>
<td>$\gamma \rightarrow \alpha + \beta$</td>
<td><img src="image" alt="Eutectoid Diagram" /></td>
</tr>
<tr>
<td>Peritectoid</td>
<td>$\alpha + \beta \rightarrow \gamma$</td>
<td><img src="image" alt="Peritectoid Diagram" /></td>
</tr>
<tr>
<td>Peritectic</td>
<td>$\alpha + L \rightarrow \beta$</td>
<td><img src="image" alt="Peritectic Diagram" /></td>
</tr>
<tr>
<td>Monotectic</td>
<td>$L_1 \rightarrow L_2 + \alpha$</td>
<td><img src="image" alt="Monotectic Diagram" /></td>
</tr>
</tbody>
</table>

## Types of three-phase reactions in metals
Microstructure of:

- Austenite
- Ferrite
- Graphite or graphitic carbon in low carbon steel
- Perlite + Fe₃C in GB
- Spheroidized Fe₃C in a matrix of ferrite
Eutectoid vs. eutectic transformation

- Ferrite + Fe₃C
- Austenite + Fe₃C

Perlite

Ledebutite
Phases in peritectic steels

Phases in hypoeutectoid steels

Phases in eutectoid steels

Phases in hypereutectoid steels
Phase transformations do not occur at the same temperature in heating as in cooling.

- In heating, the Ac temperatures are somewhat higher than equilibrium temperatures Ae.
- On cooling the Ar temperatures are lower than equilibrium temperatures Ae.
- The difference in temperature between the Ac and the Ar can vary in some cases as much as 24°C.
Austenite transform to perlite when it is cooled slowly below the $A_r$ critical temperature.

When austenite is more rapidly cooled, however, this transformation is retarded.

As the cooling rate is increased, the transformation temperature is lowered which results in the formation of the micro-constituents that are shown in table w:

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearlite</td>
<td>705 to 535°C (1300 to 1000°F)</td>
</tr>
<tr>
<td>Bainite</td>
<td>535 to 230°C (1000 to 450°F)</td>
</tr>
<tr>
<td>Martensite</td>
<td>Below 230°C (450°F)</td>
</tr>
</tbody>
</table>

Constituents formed during supercooling of austenite
Time-Temperature-Transformation

Cooling rates:
A-5°C, B-400°C, D-50°C

C-critical cooling rate, i.e. minimal cooling rate that must be maintained to obtain a completely martensitic microstructure.
Types of heat treatment

Portion of the Fe-C diagrams showing temperature ranges for:

Process & recrystallization annealing
stress relieving and spheroidizing

full annealing, normalizing, hot working
and homogenizing

<table>
<thead>
<tr>
<th>Heat Treatment Process</th>
<th>Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full annealing</td>
<td>Ferrite and pearlite</td>
</tr>
<tr>
<td>Isothermal annealing</td>
<td>Ferrite and pearlite</td>
</tr>
<tr>
<td>Normalizing</td>
<td>Ferrite and pearlite</td>
</tr>
<tr>
<td>Spheroidizing</td>
<td>Ferrite and carbide</td>
</tr>
<tr>
<td>Quenching and tempering</td>
<td>Tempered martensite</td>
</tr>
<tr>
<td>Martempering</td>
<td>Tempered martensite</td>
</tr>
<tr>
<td>Austempering</td>
<td>Bainite</td>
</tr>
<tr>
<td>Dual-phase</td>
<td>Ferrite and martensite</td>
</tr>
</tbody>
</table>
Thermo-Mechanical Processing of Steels

Steel for car body applications
Factors that decides about formability of sheets:

- The langford coefficient ($R$) – deep drawibility
- The planar anisotropy ($\Delta R$) – earing
- The strain hardening coefficient ($n$) – resistance to strain localization

Texture control (anisotropy and good drawibility) is crucial
Steel for car body applications
Interstitial-free steels

The influence of Ti, Ta, Nb content on $\bar{R}$-value (normal anisotropy coefficient). The graph shows the deficit excess in at% of the alloying elements relative to the C+N content.

The larger the $\bar{R}$ value the better deep drawibility

The problem with these steels is to obtain a fine grain size after hot rolling
Steel for car body applications
low carbon steels

Deep drawibility as a function of the ultimate tensile strength (UTS) for several steel grades used in car body applications.

**Strenght increase:**

- **IF-HSS** – IF high strength steels (+ Nb, Ta & Ti)
- **BH** – bake hardening steels
- **Rephos** – rephosphorised steels (P-0.04-0.08%)
- **HSLA**-high-strength low-alloy steels (+ Nb & Ti)
- **DP**-**Dual Phase** (ferrite + 10-20% martensite)
- **TRIP**-**Transformation-Induced Plasticity** ferrite, bainite & retained austenite)
Steel for car body applications - low carbon steels

Composition and properties of typical dual phase steel

<table>
<thead>
<tr>
<th>Composition in wt%</th>
<th>0.1 C</th>
<th>0.2 Si</th>
<th>0.7 Mn</th>
<th>0.05 P</th>
<th>0.04 Al</th>
<th>0.005 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties</td>
<td>UTS: 600 MPa</td>
<td>YS: 350 MPa</td>
<td>$\bar{R}$: 0.9</td>
<td>E: 27%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Processing of dual phase (DP) steel by cold rolling and two-step annealing treatment:

- Ferrite + 10-20% austenite
- Ferrite + 10-20% martensite
Steel for car body applications - low carbon steels

Composition and properties of typical TRIP steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Al</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>N</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 Si</td>
<td>0.11</td>
<td>1.50</td>
<td>0.04</td>
<td>1.53</td>
<td>0.008</td>
<td>0.006</td>
<td>0.0035</td>
<td>Girault et al. [2001]</td>
</tr>
<tr>
<td>0.8 Si</td>
<td>0.12</td>
<td>0.78</td>
<td>0.04</td>
<td>1.51</td>
<td>0.010</td>
<td>0.006</td>
<td>0.0035</td>
<td>Girault et al. [2001]</td>
</tr>
<tr>
<td>Si–Al</td>
<td>0.115</td>
<td>0.49</td>
<td>0.38</td>
<td>1.51</td>
<td>0.003</td>
<td>0.009</td>
<td>0.030</td>
<td>Jacques et al. [2001]</td>
</tr>
<tr>
<td>1.5 Al</td>
<td>0.110</td>
<td>0.06</td>
<td>1.50</td>
<td>1.55</td>
<td>0.012</td>
<td>0.007</td>
<td>0.017</td>
<td>Jacques et al. [2001]</td>
</tr>
</tbody>
</table>

TRIP steels can be considered as a further development of dual phase grades.

Starting structure – mixture of ferrite and austenite (high temperature annealing -1st) → fast cooling

Final structure – austenite, ferrite, bainite (formed during low temperature annealing - 2nd) and martensite (formed during further rapid cooling to room temp.)
Steel for car body applications - low carbon steels (~0.1%C)

TRIP steel – cold rolling route

Processing scheme and structural evolution during the two-step heat treatment of TRIP steel
Steel for car body applications - low carbon steels (~0.1%C)

TRIP steel

Illustration of the structural changes in TRIP steel during the second isothermal treatment (above) and transformation products after rapid cooling.
Steel for car body applications - low carbon steels (~0.1% C)

TRIP steel – hot rolling route

- Hot rolling in the austenite region or in the intercritical (\(\alpha+\gamma\)) region and cooled (quench finish temperature \(\sim 400^\circ C\)),

- During annealing in the bainite region the residual austenite will partially transform into bainite, and the rejected carbon stabilize retaining austenite,

- After further cooling some austenite will be retained at RT

`Consumption` of retained austenite during a uniaxial tensile test
Steel for car body applications - low carbon steels (~0.1%C) 

TRIP steel

Compilation of mechanical properties of some selected TRIP steels

<table>
<thead>
<tr>
<th>Type</th>
<th>C (wt%)</th>
<th>Si (wt%)</th>
<th>Mn (wt%)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>$\varepsilon_{\text{total}}$ (%)</th>
<th>Lüders strain</th>
<th>$n$ (5–15%)</th>
<th>$\bar{R}$</th>
<th>LDR</th>
<th>UTS × $\varepsilon_{\text{total}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>0.006</td>
<td></td>
<td>0.12</td>
<td>133</td>
<td>298</td>
<td>51</td>
<td>0</td>
<td>0.24</td>
<td>2.1</td>
<td>2.34</td>
<td>$1.5 \times 10^4$</td>
</tr>
<tr>
<td>Dual phase</td>
<td>0.10</td>
<td>0.2</td>
<td>0.7</td>
<td>350</td>
<td>600</td>
<td>27</td>
<td>0</td>
<td>0.18</td>
<td>0.9</td>
<td></td>
<td>$1.6 \times 10^4$</td>
</tr>
<tr>
<td>TRIP 0.8 Si</td>
<td>0.12</td>
<td>0.78</td>
<td>1.51</td>
<td>374</td>
<td>635</td>
<td>29</td>
<td>1.1</td>
<td>0.25</td>
<td>1.14</td>
<td>2.20</td>
<td>$1.8 \times 10^4$</td>
</tr>
<tr>
<td>TRIP 1.2 Si</td>
<td>0.11</td>
<td>1.18</td>
<td>1.55</td>
<td>339</td>
<td>614</td>
<td>35</td>
<td>Yes</td>
<td>0.244</td>
<td>0.86</td>
<td></td>
<td>$2.2 \times 10^4$</td>
</tr>
<tr>
<td>TRIP 1.5 Si</td>
<td>0.11</td>
<td>1.50</td>
<td>1.534</td>
<td>452</td>
<td>698</td>
<td>31</td>
<td>1.5</td>
<td>0.24</td>
<td>1.0</td>
<td>2.24</td>
<td>$2.2 \times 10^4$</td>
</tr>
<tr>
<td>TRIP 1.9 Si</td>
<td>0.14</td>
<td>1.94</td>
<td>1.66</td>
<td>530</td>
<td>890</td>
<td>32</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td>$2.6 \times 10^4$</td>
</tr>
</tbody>
</table>
Thermo-Mechanical Processing of Aluminium Alloys

Aluminium beverage cans
Aluminium beverage cans

AA3xxx

(a) A ‘three-piece’ container with welded seam, (b) ‘two-piece’ container, deep drawn or deep wall ironed
Aluminium beverage cans

- The draw and wall-ironed cup is made of an AA3xxx alloy, in most cases AA3104 (~1%wt.Mn and ~1%wt.Mg).
- The lid – AA5xxx alloy, e.g. AA5182 (4-5%wt. Mg and 0.3-0.4 %wt.Mn)
- The pull ring is fabricated from another high-Mg AA5xxx alloy.
Aluminium beverage cans

Scheme of the second deep-drawing pass, the three-wall ironing passes and the formation of a dome-shaped bottom in the ‘bodymaker’ press.

Schematic showing the variation in the wall thickness along the height of the cup. The thickness of the bottom \( d_0 \) is close to original sheet thickness.
Aluminium beverage cans

Influence of some texture components on earing

<table>
<thead>
<tr>
<th>Texture component</th>
<th>Name</th>
<th>Earling</th>
</tr>
</thead>
<tbody>
<tr>
<td>{100}&lt;001&gt;</td>
<td>Cube</td>
<td>4 ears; 0/90/180/270°</td>
</tr>
<tr>
<td>{110}&lt;001&gt;</td>
<td>Goss</td>
<td>2 ears; 0/180°</td>
</tr>
<tr>
<td>{110}&lt;112&gt;</td>
<td>Brass</td>
<td>4 ears; 45/135/225/315°</td>
</tr>
<tr>
<td>{112}&lt;111&gt;</td>
<td>Copper</td>
<td>4 ears; 45/135/225/315°</td>
</tr>
<tr>
<td>{123}&lt;412&gt;</td>
<td>R. or S</td>
<td>4 ears; 45/135/225/315°</td>
</tr>
</tbody>
</table>

Illustration of how 45° and 0/90° ears can compensate each other

Components of the β-fibre
The 0/90° ears are gradually compensated by the 45° ears as a function of increasing cold rolling.
Aluminium beverage cans

Influence of large particles (>2.5 µm) on the texture after hot rolling and recrystallization

Weaker cube texture due to PSN and smaller grain size

Very large particles can promote fracture during can forming operations
Aluminium beverage cans

Typical production scheme for can body sheet

Direct casting or electromagnetic casting (750mm x 180mm)

Homogenization

\[ 550^\circ C, t = 10 \text{ à } 14 \text{u} \]

\[ 500^\circ C \]

\[ 25 \text{mm} \]

\[ 300^\circ C \]

\[ \text{reversible mill} \]

\[ 25 \text{mm} \]

\[ \text{tandem mill} \]

\[ 2.5 \text{mm} \]

\[ \text{recrystallisation in the coil} \]

\[ \text{cold rolling (88\%)} \]

\[ \approx 0.3 \text{mm} \]