High Strength Steels

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Tata Steel
IISc, Bangalore – 11th July 2012

There’s a little bit of SAIL in everybody’s life

An Advertisement ..... !!
There’s a little bit of steel in everybody’s life

A Fact

“little bit of steel” → “lot of steel”

More appropriate

Application of Steel

Every aspect of human civilization
Application of Steel

Application of Steel
Application of Steel

Application of Steel
Application of Steel

Application of Steel
Application of Steel

Selection of Steel

• Matching between property and application
High Strength Steel

Application

• Construction
• Automotive – structural components

Steels for Construction

• C-Mn steels
• Microalloyed (HSLA) steels

• Key points
  – Strength
  – Toughness
  – Weldability
Strength and Ductility

Impact Transition Curve
Effect of Carbon Content on Toughness

Effect of Grain Refinement on Toughness
Effect of Strengthening Mechanism

- Solid solution hardening by carbon
- Strengthening by dislocations
- Precipitation hardening
- Grain refinement

Increase of yield strength in MPa vs. Change of transition temperature in °C

Weldability – Cold Crack Susceptibility

- CE ≤ 0.4% → low cold crack susceptibility
- Preheating required for high hardenability

CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15}
Steel Design

- Decreasing carbon content
  - Improves weldability
  - Improves toughness
  - Decreases strength
- Increase strength
  - Grain refinement
  - Precipitation hardening

Grain Refinement

- Retardation of austenite grain growth by AlN
Effect of Microalloying on Austenite Recrystallisation

0.04 mass% Nb
0 mass% Nb

Maximum strain induced NbC precipitation

Austenite Grain Coarsening

- Effect of microalloying

Austenite grain diameter in µm

Temperature in °C
Effect of Microalloying on YS and DBTT

- S355 with 0.05% Nb or 0.1% V or 0.1% Ti

Effect of FRT on Transformation

- High finishing rolling temperature
- Conventional rolling
- Controlled rolling
- Low finishing rolling temperature
- Accelerated cooling

γ microstructure before transformation

γ grain

γ matrix

defor.mation band

- Additional nuclei due to controlled rolling or accelerated cooling

Partially transformed microstructure

Magnified
Steels for Automotive Application

Car - Older Days

- A machine that moved on road
- Concept of fuel efficiency - not quite an issue
A Luxurious Asset

Giant Cars - Fuel Guzzlers
Modern Cars

And Now ..........
The Driving Force

- Fuel efficiency: A vital concept nowadays
- Emission norms
- Driving conditions
  - Heavy traffic
  - Road condition
  - Parking space
- Safety consciousness
- Price and maintenance cost (overall expenditure)
- Reach of middle class consumer

Desirable Properties

- Strength
- Toughness
- Dent resistance
- Formability
  - Drawing
  - Stretching
  - Bending
- Weldability
- Surface
Steels for Automotive Application

Classification
# Steels for Automotive Application

- Drawing and deep drawing quality steels
- Bake hardening steels
- C-Mn Steels
- Microalloyed steels
- Dual phase steel
- TRIP steel

<table>
<thead>
<tr>
<th>Part</th>
<th>Required properties</th>
<th>Panel rigidity</th>
<th>Dent resistance</th>
<th>Member rigidity</th>
<th>Fatigue strength</th>
<th>Crush strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer panels</td>
<td>Door outer, etc.</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
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<tr>
<td>Inner panels</td>
<td>Door, etc.</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td>Structural parts</td>
<td>Front rail, rear piller, etc.</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Front side member, side sill, etc.</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Door reinforcement, etc.</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td></td>
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<tr>
<td>Underbody parts</td>
<td>Suspension arm, disc wheel, etc.</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td></td>
</tr>
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</table>

Main controlling factors apart from thickness of steels: Young’s modulus, Yield strength, Young’s modulus, Tensile strength, Tensile strength.

## ULSAB Concept

<table>
<thead>
<tr>
<th>Product</th>
<th>YS (MPa)*</th>
<th>UTS (MPa)*</th>
<th>Total EL (%)</th>
<th>n-value (5-15%)</th>
<th>r-bar*</th>
<th>Application Code</th>
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<tbody>
<tr>
<td>Mild 140/370</td>
<td>140</td>
<td>270</td>
<td>38-44</td>
<td>0.23</td>
<td>1.8</td>
<td>A.C.F</td>
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<tr>
<td>BH 210/340</td>
<td>210</td>
<td>340</td>
<td>34-39</td>
<td>0.18</td>
<td>1.8</td>
<td>B</td>
</tr>
<tr>
<td>BH 260/370</td>
<td>260</td>
<td>370</td>
<td>29-34</td>
<td>0.13</td>
<td>1.6</td>
<td>B</td>
</tr>
<tr>
<td>IF 260/410</td>
<td>260</td>
<td>410</td>
<td>34-38</td>
<td>0.20</td>
<td>1.7</td>
<td>C</td>
</tr>
<tr>
<td>DP 280/600</td>
<td>280</td>
<td>600</td>
<td>30-34</td>
<td>0.21</td>
<td>1.0</td>
<td>B</td>
</tr>
<tr>
<td>IF 300/420</td>
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<td>420</td>
<td>29-36</td>
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<td>1.6</td>
<td>B</td>
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<tr>
<td>DP 300/500</td>
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<td>500</td>
<td>30-34</td>
<td>0.16</td>
<td>1.0</td>
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<tr>
<td>HSLA 350/450</td>
<td>350</td>
<td>450</td>
<td>23-27</td>
<td>0.23</td>
<td>1.0</td>
<td>A,B,S</td>
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<tr>
<td>DP 350/600</td>
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<td>600</td>
<td>24-30</td>
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<td>1.1</td>
<td>A,B,C,W,S</td>
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<tr>
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<td>700</td>
<td>19-25</td>
<td>0.14</td>
<td>1.0</td>
<td>A,B</td>
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<tr>
<td>TRIP 450/800</td>
<td>450</td>
<td>800</td>
<td>26-32</td>
<td>0.24</td>
<td>0.9</td>
<td>A,B</td>
</tr>
<tr>
<td>HSLA 490/600</td>
<td>490</td>
<td>600</td>
<td>21-26</td>
<td>0.13</td>
<td>1.0</td>
<td>W</td>
</tr>
<tr>
<td>DP 500/800</td>
<td>500</td>
<td>800</td>
<td>14-20</td>
<td>0.14</td>
<td>1.0</td>
<td>A,B,C,W</td>
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<tr>
<td>SF 570/640</td>
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<td>640</td>
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<td>0.08</td>
<td>1.0</td>
<td>S</td>
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<tr>
<td>CP 700/900</td>
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<td>800</td>
<td>10-15</td>
<td>0.13</td>
<td>1.0</td>
<td>B</td>
</tr>
<tr>
<td>DP 700/1000</td>
<td>700</td>
<td>1000</td>
<td>12-17</td>
<td>0.09</td>
<td>0.9</td>
<td>B</td>
</tr>
<tr>
<td>Mart 950/1200</td>
<td>950</td>
<td>1200</td>
<td>5-7</td>
<td>0.07</td>
<td>0.9</td>
<td>A,B</td>
</tr>
<tr>
<td>MnB**</td>
<td>1200</td>
<td>1800</td>
<td>4-6</td>
<td>na</td>
<td>na</td>
<td>S</td>
</tr>
<tr>
<td>Mart 1250/1520</td>
<td>1250</td>
<td>1520</td>
<td>4-6</td>
<td>0.07</td>
<td>0.9</td>
<td>A</td>
</tr>
</tbody>
</table>

Different Steel Grades in Car Body

Car body
Porsche Cayenne

Application of high strength steels with UTS up to 1000 MPa

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>590TRIP</td>
<td>590 high-burring</td>
</tr>
<tr>
<td>780</td>
<td>780 high-burring</td>
</tr>
<tr>
<td>800</td>
<td>800 high-burring</td>
</tr>
<tr>
<td>980 ~</td>
<td>980 high-burring</td>
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</table>

Components and Steel Grades

<table>
<thead>
<tr>
<th>[TS] MP (kgf/mm²)</th>
<th>Soft sheet steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>340 ~ 370 (35 ~ 38)</td>
<td></td>
</tr>
<tr>
<td>390 ~ 440 (40 ~ 45)</td>
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</tr>
<tr>
<td>590 (80)</td>
<td></td>
</tr>
<tr>
<td>690 (70)</td>
<td></td>
</tr>
<tr>
<td>780 (80)</td>
<td></td>
</tr>
<tr>
<td>980 ~ (100 ~)</td>
<td></td>
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</table>
Trend of Usage of HSS

Vehicle Weight Reduction

OPEL CORSA - Material Distribution BIW

Old CORSA:
- > 200 MPa: 23%
- > 300 MPa: 18%
- > 500 MPa: 11%
- > 1000 MPa: 4%
- Mild Steel: 37%
- Aluminum: 2%

New CORSA:
- > 200 MPa: 18%
- > 300 MPa: 18%
- > 500 MPa: 11%
- > 1000 MPa: 4%
- Mild Steel: 32%
- Aluminum: 1%
Press Forming – Deformation Modes

Drawing Operation

CONVENTIONAL FIRST DRAW

1 BLANK HOLDER
2 PUNCH
3 DIE
4 KNOUT
Drawing – Material Property

• Most essential – maximum resistance against thinning, when a sheet metal is subjected to deep drawing
• Drawability is determined by a quantity called plastic strain ratio (r value)
• This is a ratio of true strain values in width and thickness directions ($r = \varepsilon_w/\varepsilon_t$)
• Strong influence of ND//{111} texture formation

Lankford parameter

$r = \varepsilon_w/\varepsilon_t$

$\bar{r} = \frac{r_{t} + 2r_{45^\circ} + r_{t}}{4}$

Normal anisotropy: Low $\varepsilon_t$ value means less deformation in thickness direction, high r value and larger cup depth
Deep drawn cups

Auto body panels
Stretching of sheet metal

- MOVABLE GRIPPERS
- UPPER DIE BLOCK
- WORKPIECE
- LOWER DIE BLOCK

OPEN POSITION
STRETCHED POSITION
FORMED POSITION

Stretchability

- Another important factor - indicates the ability of distributing the strain, thereby preventing localised thinning and cracking

- Expressed as strain hardening exponent or $n$ value: $\sigma = k\varepsilon^n$ ($k$ is a constant)
Drawing Quality Steels

- Al-killed EDD steel
- Plain low C-Mn steel (C ~ 0.03 – 0.05%)
- Ideal for batch annealing
- AlN precipitation during annealing – \{111\} texture

<table>
<thead>
<tr>
<th>Grades</th>
<th>YS</th>
<th>UTS</th>
<th>%El</th>
<th>r-bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQ</td>
<td>200</td>
<td>330</td>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>EDD</td>
<td>170</td>
<td>300</td>
<td>45</td>
<td>1.75</td>
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</table>

Interstitial Free Steels

- Developed in the decade of 70s
- Higher productivity – continuous annealing
- Ultra low carbon composition
- Suitable for heavy drawing operations
- High strength IF steel – addition of Mn and P

<table>
<thead>
<tr>
<th>Grades</th>
<th>YS</th>
<th>UTS</th>
<th>%El</th>
<th>r-bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>140</td>
<td>290</td>
<td>50</td>
<td>2.0</td>
</tr>
<tr>
<td>IFHS</td>
<td>180-290</td>
<td>340-440</td>
<td>32-42</td>
<td>1.3-1.7</td>
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</tbody>
</table>
**Principle of IF Steel**

- **Nitride and carbide formation:**
  - The steel becomes free of interstitial elements
- **TiS:** S in steel is fixed
- **$\text{Ti}_4\text{C}_2\text{S}_2$ formation:** Very effective but requires critical adjustment of temperature
- **TiC, NbC formation:** Favoured by high CT

**High Strength IF Steel**

- Mn and P addition
- Strength can be as high as 450 MPa
- Both affect drawability
- Change of precipitation sequence
- FeTiP precipitation – harmful
- Effect of P – secondary work embrittlement
- Slight addition of boron takes care of the problem
Bake hardening Steel

- YPE removal by skin passing after annealing
- Work hardening (Forming)
- Paint baking treatment (typically at 170°C for 20 min): dislocation locking by solute C
- Higher YP - return of yield point

Bake hardening Steel

- ULC steel
- Unstabilised or partially stabilised
- Solid solution strengthened (Mn, P)
- Controlled strain aging
- High YS after press forming
- Improved dent resistance
- Good drawability
- External components

<table>
<thead>
<tr>
<th>Grades</th>
<th>YS</th>
<th>UTS</th>
<th>%El</th>
<th>r-bar</th>
<th>BH</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH180</td>
<td>180</td>
<td>300</td>
<td>45</td>
<td>1.6</td>
<td>30</td>
</tr>
<tr>
<td>BH220</td>
<td>220</td>
<td>340</td>
<td>40</td>
<td>1.5</td>
<td>30</td>
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<tr>
<td>BH260</td>
<td>260</td>
<td>380</td>
<td>35</td>
<td>1.4</td>
<td>30</td>
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</table>
Various Strengthening Mechanisms

How can steel be made even stronger?

- Strengthening solid solubility
- Strengthening precipitation
- Strengthening transformation

<table>
<thead>
<tr>
<th>Strength</th>
<th>270</th>
<th>390</th>
<th>590</th>
<th>780</th>
<th>980</th>
<th>1180</th>
<th>MPa</th>
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<tbody>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Microalloyed Steels for Auto Body

- Load bearing, structural components
- Intricate drawing is not required
- Typical constituents
  - C ~ 0.06-0.12%
  - Mn ~ 0.5-1.5%
- Typical microalloying:
  - Ti ~ 0.03-0.08%
  - Nb ~ 0.03-0.08%
  - V ~ 0.05-0.1%
HSLA Steel - Principle

• Solid solution strengthening:
  – Ti and Nb, both have solid solution hardening effect
  – Suitable for strength level of 500-520 MPa
• Grain refinement: Solute drag effect of Nb
• Precipitation hardening:
  – Precipitation of fine carbides
  – Suitable for continuous annealing route
  – Strength level may be up to 590 MPa

YS of HSLA Steels

<table>
<thead>
<tr>
<th>YS (MPa)</th>
<th>%EI (GL=80mm, t&lt;3mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td></td>
</tr>
<tr>
<td>550</td>
<td></td>
</tr>
<tr>
<td>580</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>420</td>
<td></td>
</tr>
<tr>
<td>360</td>
<td></td>
</tr>
<tr>
<td>360</td>
<td></td>
</tr>
<tr>
<td>329</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td></td>
</tr>
<tr>
<td>280</td>
<td></td>
</tr>
<tr>
<td>240</td>
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</table>
## HSLA - Typical Properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>%EI</th>
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<tbody>
<tr>
<td>HSLA 280</td>
<td>280-340</td>
<td>380-440</td>
<td>≥ 28</td>
</tr>
<tr>
<td>HSLA 320</td>
<td>320-380</td>
<td>410-480</td>
<td>≥ 24</td>
</tr>
<tr>
<td>HSLA 360</td>
<td>360-430</td>
<td>450-520</td>
<td>≥ 21</td>
</tr>
<tr>
<td>HSLA 400</td>
<td>400-500</td>
<td>460-590</td>
<td>≥ 18</td>
</tr>
<tr>
<td>HSLA 420</td>
<td>420-500</td>
<td>490-570</td>
<td>≥ 20</td>
</tr>
<tr>
<td>HSLA 500</td>
<td>500-590</td>
<td>570-670</td>
<td>≥ 15</td>
</tr>
<tr>
<td>HSLA 550</td>
<td>550-650</td>
<td>620-720</td>
<td>≥ 14</td>
</tr>
<tr>
<td>HSLA 700</td>
<td>700-800</td>
<td>750-910</td>
<td>≥ 14</td>
</tr>
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</table>

### Advantages of HSLA Steels

- Significant weight saving for structural components and reinforcements
- Suitable for internal structural parts, such as
  - chassis components
  - suspension arms
  - shock absorber cups
  - longitudinal beams
  - cross members
HSLA - Application

Rear cross-member

Front reinforcement (in DP) + Shock absorber cup (in HSLA)

Advanced High Strength Steels

[Graph showing calculated absorbed energy (kJ) vs. total elongation (%) with different steel types: 618MPa-DP, 644MPa-TRIP, 636MPa-HSLA, 348MPa-mild steel, and 487MPa-solution hardened]
Energy Absorption

Passenger Safety
HSS – Material Design

Family of Multiphase Steels
Dual Phase Steels

• Typical constituents:
  – C: 0.1-0.2% (higher than usual ‘low carbon’ compositions)
  – Mn: 1-2%
  – Si: ~ 0.4%
• Other elements: Mo – enhances hardenability and ensures transformation of remaining austenite to martensite

DP Steel - Principle

• Intercritical cooling from austenite
• Partial transformation: austenite to ferrite
• Fast cooling: Transformation of the remaining austenite to martensite
DP Steel - Microstructure

Approximately 20% martensite in ferrite matrix

DP Steel - Typical Properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>%El</th>
<th>BH (MPa)</th>
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</thead>
<tbody>
<tr>
<td>DP 450</td>
<td>260-340</td>
<td>450-530</td>
<td>≥27</td>
<td>30</td>
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<tr>
<td>DP 500</td>
<td>300-380</td>
<td>500-580</td>
<td>≥25</td>
<td>30</td>
</tr>
<tr>
<td>DP 590</td>
<td>320-400</td>
<td>600-700</td>
<td>≥21</td>
<td>30</td>
</tr>
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<td>DP 780</td>
<td>450-550</td>
<td>780-900</td>
<td>≥15</td>
<td>30</td>
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<td>DP 980</td>
<td>550-700</td>
<td>980-1100</td>
<td>≥10</td>
<td>30</td>
</tr>
<tr>
<td>DP 600</td>
<td>300-470</td>
<td>580-670</td>
<td>≥20</td>
<td>30</td>
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<tr>
<td>DP 800</td>
<td>560-700</td>
<td>750-900</td>
<td>≥14</td>
<td>30</td>
</tr>
</tbody>
</table>
DP Steel - Advantages

• Low YS/UTS ratio
• High strain hardening rate: strain distribution during forming
• Combination of strength and ductility
• No YP phenomenon
• Exhibits bake hardening during paint baking

DP Steel - Application

Front reinforcement

Beam

Wheel
TRIP Steel

• TRIP: Transformation Induced Plasticity
• Typical composition:
  – C: 0.25%
  – Mn: 2%
  – Si: 1.5%
  – Other elements: Ni, Mo, Cr

TRIP Steel - Principle

• The microstructure contains ferrite, bainite and about 15% retained austenite
• This is achieved by
  – adjustment of the martensitic transformation temperatures, by suitable composition
  – appropriate thermo-mechanical treatment, ensures the presence of retained austenite, which is a metastable phase
TRIP Steel - Principle

- During subsequent forming, plastic zones are created at the tip of the cracks
- The metastable austenite phase transforms into martensite, due to the induced strain
- The localized volume expansion associated with the transformation of the retained austenite to martensite during deformation delays the onset of necking and thereby results in a high uniform elongation

TRIP – Enhancement of Ductility
TRIP Steel
Microstructure

Typical CR TRIP
(about 18%
retained austenite)

TRIP Steel - Typical Properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>%El</th>
<th>n</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIP 600</td>
<td>380-480</td>
<td>590-700</td>
<td>≥26</td>
<td>≥0.20</td>
<td></td>
</tr>
<tr>
<td>TRIP 700</td>
<td>410-510</td>
<td>690-800</td>
<td>≥24</td>
<td>≥0.19</td>
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<tr>
<td>TRIP 800</td>
<td>450-550</td>
<td>780-900</td>
<td>≥23</td>
<td>≥0.18</td>
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</tr>
<tr>
<td>TRIP 1000</td>
<td>&gt; 500</td>
<td>980-1100</td>
<td>≥18</td>
<td>≥0.14</td>
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<tr>
<td>TRIP 800</td>
<td>&gt; 450</td>
<td>780-900</td>
<td>≥21</td>
<td></td>
<td></td>
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</tbody>
</table>

Combined WH + BH: Approximately 170 MPa
Martensitic Steel

- The austenite that exists during hot rolling or annealing is transformed almost entirely to martensite during quenching on the run-out table or in the cooling section of the annealing line
- Often subjected to post-quench tempering to improve ductility
- Highest strengths, up to 1500 MPa UTS

Quench and Partitioning

- A new concept in AHSS
- C partitioning in austenite phase
- Higher stability of austenite
Stamping of AHSS

Hemispherical punch stretching

Box stamping

TWIP Steel

- Twin induced plasticity
- Combination of strength and ductility
- Delayed necking phenomenon
- Increased strength and ductility
- High Mn steel – austenite matrix
TWIP Steel

- High uniform elongation

[TWIP steel (X5 Mn Al Si 25 3 3)]

Sample after twisting by 1080° (T = 20 °C)

Tensile Behaviour of TWIP Steel

[Cornette et al., SAE Intl Conf. Proc., SP-1951, 2005-01-1327, pp. 65]
Composition and Microstructure

- Stable austenite phase
- Alloying – Mn addition
- Control of SFE

Strength and Elongation

- Strength: TRIP > TWIP
- Elongation: TWIP > TRIP

<table>
<thead>
<tr>
<th>Mn</th>
<th>Al</th>
<th>Si</th>
<th>C</th>
<th>Fe</th>
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<tr>
<td>23.8</td>
<td>2.7</td>
<td>3.0</td>
<td>$6 \times 10^{-4}$</td>
<td>Balance</td>
</tr>
<tr>
<td>33.0</td>
<td>2.93</td>
<td>3.0</td>
<td>$6 \times 10^{-4}$</td>
<td>Balance</td>
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</table>
Advanced Fabrication Techniques for AHSS

- Tailor welded blank (TWB)
- Hydroforming
TWB

1.5 mm 210B Mpa
Uncoated

1.1 mm 340 Mpa
HD Galvanized

0.8 mm 180A Mpa
Uncoated

Sheet Hydroforming

Fluid Chamber

Draw Bead

Blank

Punch

Blank

(1)

(2)

(3)

(4)
Tube Hydroforming

1. Body shell
2. Driving shaft
3. Assembled camshaft
4. Exhaust systems
5. Engine cooling system
6. Radiator frame
7. Safety guards
8. Engine bearer
9. Integral member
10. Cross member
11. Frame structure parts
12. Axle elements
13. Plumbing fixtures
14. Oven – door handles

Thank you