High Strength Steel for Steel Constructions

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- N / NE
- Q + T
- TM

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High strength steel – What’s that?

End of 1920: Introduction of the steel grade St52 (S355) for bridge-building (Prof. Klöppel)

→ St52 was called a high strength steel for a long period

Now:

S355 is a standard material for bridge-building

→ Definition of „high strength“ depends on the technical development

Today´s Definition: high strength steel

⇔ Steel with $R_{eH} > 355$ MPa
Introduction

High strength steel

Weight reduction

Economical processing
DELIVERY CONDITIONS

AR   TM   Q+T   N
Delivery Conditions

**Process Diagram**

- **Temperature**
  - $\gamma_{rec}$
  - $\gamma_{not\_rec}$
  - $\alpha + \gamma$
  - $\alpha$

- **Time**
  - "as rolled" ("AR")
  - $A_{c3}$
  - $T_{N}$
  - $A_{r3}$
  - $M_{S}$
  - $A_{r1}$
  - $T_{M}$ ($\gamma$)
  - $T_{M}$ ($\gamma + \alpha$)
  - ACC
  - TM+ ACC
  - TM+ DQ, QST

- **Steps**
  - A: Hot Rolling
  - B: Air
  - C: Water
  - D: TM ($\gamma$)
  - E: TM ($\gamma + \alpha$)
  - F: ACC
  - G: TM+ ACC

- **Notations**
  - "TM(CP)"
  - Time axis labels: N, Q

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Delivery Conditions

AR

hot rolling
AR            As Rolled

Classical rolling

Transition area: 
\( \alpha\text{-Fe} - \gamma\text{-Fe} \)

Cooling on calm air

Delivery Conditions

1100 - 1200°C
900°C
700°C

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Delivery Conditions

hot-rolling + Normalising
Normalising

Classical rolling

Cooling on calm air

Transition area: $\alpha$-Fe - $\gamma$-Fe

Delivery Conditions
Normalising rolling

Phase 1

1100 - 1200°C

Phase 2

(T > 900°C)

Transition area: \(\alpha\)-Fe - \(\gamma\)-Fe

Definition: After an additional normalising in the furnace, the properties of a normalised rolled plate must fulfil the mechanical requirements of the standard.

Cooling on calm air
hot-rolling  Quenching + Tempering
Q+T → Quenching + Tempering

Classical rolling

Quenching

Tempering

core

surface

Delivery Conditions
**Q+T Effect of quenching**

**[℃]**

- **1390**
  - Carbon solved in the lattice
  - Austenite

- **910**
  - Ferrite + Cementite (Carbon can leave the lattice)
  - Martensite (Carbon stays in the lattice, distorted structure)

**Delivery Conditions**

- **Fast cooling:**
  - Ferrite + Perlite
  - Martensite

- **Slow cooling:**
  - Ferrite + Perlite
Q+T Effect of tempering

Charpy-V [J] vs. Temperature [°C]

- A4
- A3
- A2
- A1
- quenched
Q+T  Effect of tempering

![Graph showing the effect of tempering on strength](image)

- **Delivery Conditions**
- **Strength [MPa]**
- **Temper-Parameter**

<table>
<thead>
<tr>
<th>Temper-Parameter</th>
<th>Yield point</th>
<th>Ultimate strength</th>
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<tbody>
<tr>
<td>quenched</td>
<td></td>
<td></td>
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<tr>
<td>A1</td>
<td></td>
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<tr>
<td>A3</td>
<td></td>
<td></td>
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<tr>
<td>A4</td>
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</table>
Q+T Typical applications

Delivery Conditions
Delivery Conditions

Thermo-Mechanical rolling

**Diagram:**
- **A:** Hot Rolling
- **B:** Process
- **C:** Delivery Conditions
- **D:** TM
- **E:** TM (γ)
- **F:** TM (γ+α)
- **G:** TM+ ACC
- **Q:** TM+ DQ, QST

**Key Points:**
- γ_{rec}
- γ_{not-rec}
- α + γ
- “as rolled” ("AR")
- M_{s}
- T_{N}
- Water
- Air
- Ar_{s}
- Ar_{1}
- ACC
- "TM(CP)"

**Legend:**
- N
- Q

**Note:**
- Time

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**Delivery Conditions**

**TM** → **Thermomechanical rolling**

- **Phase 1** (T > 900°C)
- **Phase 2** (T > 700°C) with waiting time
- **Phase 3**
  - **Accelerated cooling with water (ACC)**
  - **Cooling on calm air**

**T** = Temperature

**t** = Time
**TM** Thermomechanical rolling

- **γ (coarse)** recrystallised
- **γ (fine)** formed
- **α**

- Heating
- Grain refinement
- Final rolling
- Accelerated cooling
- Cooling on air
- Tempering
Advantages of TM-steel - Processing

PROPERTIES OF TM-steel:

- TM → Fine grain
- TM → High toughness
- TM → Low carbon content
- TM → Low preheating temperatures

Excellent WELDABILITY
Advantages of TM-steel - Processing

**TM** ➔ **Fine grain**

**Hall-Petch:**

- **Grain size ↓**
- **Strength ↑**
- **Toughness ↑**
- **Excellent weldability**
Advantages of TM-steel - Processing

TM High toughness / High safety

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**Charpy-V [J]**

- **S355J2+N** (red circles)
- **S460ML** (blue squares)
- **S690QL** (black triangles)

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**Temperature [°C]**

-120, -100, -80, -60, -40, -20, 0, 20

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Advantages of TM-steel - Processing

TM  High toughness / High safety

Welding leads to toughness reduction

High toughness in the base material reduces the risk of brittle fracture and gives safety!
Advantages of TM-steel - Processing

**TM** → **High toughness / High safety**

Example: *Ilverich Rhine Bridge (Germany)*
DI-MC 460 with a thickness up to 100 mm
Charpy tested at -80°C
### TM - Low carbon content

<table>
<thead>
<tr>
<th></th>
<th>S 460 NL</th>
<th>Auxiliary Data</th>
<th>S 460 ML</th>
<th>Auxiliary Data</th>
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<tbody>
<tr>
<td><strong>acc. EN 10025-3</strong></td>
<td></td>
<td></td>
<td><strong>acc. EN 10025-4</strong></td>
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<td>&lt; 0,20</td>
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<td>&lt; 0,04</td>
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<td>&lt; 0,12</td>
<td>&lt; 0,05</td>
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<td>Mo</td>
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<td>-</td>
<td>&lt; 0,20</td>
<td>-</td>
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<tr>
<td>Ni</td>
<td>&lt; 0,80</td>
<td>0,29</td>
<td>&lt; 0,45</td>
<td>0,25</td>
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<tr>
<td>CE</td>
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<td>0,50</td>
<td></td>
<td>0,39</td>
</tr>
<tr>
<td>Pcm</td>
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<td>0,29</td>
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<td>0,20</td>
</tr>
<tr>
<td>CET</td>
<td></td>
<td>0,34</td>
<td></td>
<td>0,28</td>
</tr>
</tbody>
</table>

**Carbon equivalents:**

- **CE** = C + Mn/6 + (Cr + Mo + V)/5 + (Ni+Cu)/15
- **Pcm** = C +Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B
- **CET** = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40

Plate thickness 50 mm

Advantages of TM-steel - Processing
T_M ➔ Low preheating temperatures

**EN 1011-2**

Recommendations for arc welding of ferritic steels

\[
T_p = 697 \times \text{CET} + 160 \times \tanh\left(\frac{d}{35}\right) + 62 \times \text{HD}^{0.35} + (53 \times \text{CET} - 32) \times Q - 328
\]

- \( T_p \): Preheating temperature [°C]
- \( \text{CET} \): Carbon equivalent [%]: \( \text{CET} = C + (\text{Mn} + \text{Mo})/10 + (\text{Cr} + \text{Cu})/20 + \text{Ni}/40 \)
- \( d \): Plate thickness [mm]
- \( \text{HD} \): Hydrogen content [cm³/100 g]
- \( Q \): Heat input [kJ/mm]

Preheating is necessary to avoid:
- Excessive hardening
- Cold cracking
Advantages of TM-steel - Processing

**TM** → Low preheating temperatures

### Hydrogen content of welding consumable [cm³/100g]

**S355M**

- Plate thickness [mm]
- 75°C
- 50°C
- 25°C

**S460M**

- Plate thickness [mm]
- 100°C
- 75°C
- 50°C
- 25°C

Calculated with $Q = 2.5$ kJ/mm (submerged arc welding) and for typical CET’s
Advantages of TM-steel - Economics

TM  Cost efficiency – Low preheating

1. Reducing preheating temperatures
   - Gas consumption ↓
   - Heating time ↓

2. Avoiding preheating
   - No installations
   - No setting up time
   - No gas
Advantages of TM-steel - Economics

**Cost efficiency – Low preheating**

1. Reducing preheating temperatures
   - Gas consumption ↓
   - Heating time ↓

2. Avoiding preheating
   - No installations
   - No setting up time
   - No gas

Often underestimated, but worth to think about
Advantages of TM-steel - Economics

**TM** ➔ **Cost efficiency – Low preheating**

1. Reducing preheating temperatures
   - Gas consumption ↓
   - Heating time ↓

2. Avoiding preheating
   - No installations
   - No setting up time
   - No gas
   - Biggest potential for saving costs

Often underestimated, but worth to think about
Advantages of TM-steel - Economics

**Cost efficiency – Low preheating**

- **S355NL** $f_y = 430$ Mpa
- **S355ML** $f_y = 430$ Mpa

Possibility to avoid preheating!
- no gas consumption
- no set-up times
- higher capacity in the work shop

EN 1011-2:

$$T_{pCET} = 750 \times \text{CET} - 150$$

0.01% CET $\Leftrightarrow$ ca. 7.5°C

Graph:

- $T_{pCET}$ vs. Carbon equivalent CET [%]
  - $T_{pCET}$ range: 0 to 250°C
  - Carbon equivalent CET range: 0.2 to 0.5

**TM Cost efficiency – Low preheating**
Advantages of TM-steel - Economics

**TM** → Cost efficiency – Low preheating

**Sauertal Bridge (Germany)**

Box-girder-bridge
Length: 1195 m
Width: 27 m
11 Spans: 75 – 150 m
Tonnage: 13,000 t
Grade: S355J2+N

3000 t > 25 mm thickness
### TM Cost efficiency – Low preheating

**Alternative:**

S355J2+N > S355M  
No preheating

**Conditions:**

- 30,000 h welding time
- 15% for preheating
- 50 €/h labour costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Saving preheating times</td>
<td>A = 30,000 h x 15% x 50 €/h</td>
<td>225,000 €</td>
</tr>
<tr>
<td>B) Additional costs S355M (25 €/t)</td>
<td>B = 3,000 x 25 €/t</td>
<td>75,000 €</td>
</tr>
<tr>
<td>BENEFIT</td>
<td>C = A - B</td>
<td>150,000 €</td>
</tr>
</tbody>
</table>
Advantages of TM-steel - Economics

**Cost efficiency – Low preheating**

Low preheating temperatures are not only a matter of costs! Also in terms of job safety, low preheating temperatures are beneficial!

**NO HOT SURFACES / NO HANDLING WITH GAS / BETTER WORKING CONDITIONS**
Advantages of TM-steel - Economics

**Cost efficiency – High strength TM**

- Weight reduction
- Bigger assembling units possible
- Less holding times in the workshop
- Less welding consumables
- Reduction of welding time
- Reduction of testing time

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**TM**

- **S355NL**  $f_y = 315$ Mpa
- **S460NL**  $f_y = 430$ Mpa

- Plate thickness $\sim t^2$
- Weight reduction
- Bigger assembling units possible
- Less holding times in the workshop
- Less welding consumables
- Reduction of welding time
- Reduction of testing time

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Welding costs $\sim t^2$
Advantages of TM-steel - Economics

Cost efficiency – High strength TM

- Weight reduction (ca. 30%)
- Bigger assembling units possible
- Less holding times in the workshop
- Less welding consumables
- Reduction of welding time
- Reduction of testing time
- Avoiding/Reducing preheating
- Better weldability
- High toughness reserves
  => High safety

- TM Cost efficiency – High strength TM

S355NL $f_y = 315$ Mpa

Increasing yield strength

S460NL $f_y = 430$ Mpa

Changing delivery condition

S460ML $f_y = 430$ Mpa
Choosing the right steel

- Strength
- Delivery condition
- Toughness
Choosing the right steel

Strength

Toughness

Delivery condition
Airbus-Hangar (Frankfurt / M.)

- TM-Steel S460ML
- constant yield strength up to 120 mm
World Financial Center (Shanghai)

- TM-Steel S460M
- thickness up to 100 mm
- constant yield strength
Øresund Bridge (Denmark-Sweden)

- TM-Steel
- S460M/ML up to 80 mm
Thank you for your attention!