High Strength Steel in Hydropower: Production and Application

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• TM processed high strength steel DILLIMAX500ML

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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
General Advantages of high strength steel

High Strength Steel

- weight reduction
- economical processing

### General Advantages

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Description</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yield strength</td>
<td>2.8</td>
</tr>
<tr>
<td>3</td>
<td>Plate thickness</td>
<td>1</td>
</tr>
<tr>
<td>7,4</td>
<td>Amount of weld metal</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Cost of weld consumable</td>
<td>3.3</td>
</tr>
<tr>
<td>2,3</td>
<td>Auxilliary weld cost</td>
<td>1</td>
</tr>
<tr>
<td>5,1</td>
<td>Weighed welding cost</td>
<td>1</td>
</tr>
</tbody>
</table>
DELIVERY CONDITIONS

AR N Q+T TM
Delivery Conditions

Symposium Steel in Hydropower, Dillingen 7th April 2011
Deliver Condition AR (as rolled)

hot rolling

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Delivery Condition N

hot-rolling + Normalising
Delivery Condition Q+T

hot-rolling  Quenching + Tempering

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Q+T: the effect of quenching

Carbon solved in the lattice

Austenite

Ferrite + Cementite
(Carbon can leave the lattice)

Martensite
(Carbon stays in the lattice, distorted structure)

Slow cooling:
Ferrite + Pearlite

Fast cooling:
Martensite

20 µm

M. Steffen
High Strength steels in Hydropower
Typical applications of Q+T steels
ThermoMechanical rolling
Aims of TM processing

**TM**  ➔  Fine grain

**Hall-Petch:**

- Grain size ↓
- Strength ↑
- Toughness ↑
- Excellent weldability

Normalised (N)  ➔  TM (air)  ➔  TM (ACC)
Differentiation between normalising rolling and TM(CP)

Normalising rolling:
rolling process in which the final deformation is carried out in a certain temperature range leading to a material condition equivalent to that obtained after normalizing so that the specified values of the mechanical properties are retained even after normalizing

- material has to be suitable for a furnace normalising in the delivery condition

Thermomechanical rolling:
rolling process in which the final deformation is carried out in a certain temperature range leading to a material condition with certain properties which cannot be achieved or repeated by heat treatment alone

- heating above 580°C may impair tensile properties if such conditions are foreseen supplier should be notified in advance

Remark:
in international publications you may find both processes referred to as "controlled rolled"
General delivery programme for different delivery conditions

Plate dimensions outside this production range may be feasible upon special agreement, but restrictions may apply for certain grades/requirements.

- **N** = normalising, normalised rolled
- **TM** = thermomechanically rolled
- **Q** = quenched
- **T** = tempered

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Hydropower: actual application, thickness vs. yield strength

- Plate thickness [mm]
- Yield Strength [MPa]

- N
- TM
- Q+T
Reference thickness 50 mm

Tensile Requirements (transversal)

\[ R_{eH} : \geq 490 \text{ MPa} \quad / \quad R_m : 610 - 750 \text{ MPa} \quad / \quad A_5 : \geq 17 \%

Toughness Requirements (transversal)

at -50 °C \geq 30 \text{ J}

Chemical Composition

For the ladle analysis, the following limiting values are applicable:

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Ni</th>
<th>Cu</th>
<th>Mo</th>
<th>Cr</th>
<th>V</th>
<th>Nb</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>\leq 0.09</td>
<td>0.15 - 0.55</td>
<td>1.00 - 1.75</td>
<td>\leq 0.020</td>
<td>\leq 0.005</td>
<td>\geq 0.02</td>
<td>\leq 0.70</td>
<td>\leq 0.35</td>
<td>\leq 0.35</td>
<td>\leq 0.35</td>
<td>\leq 0.08</td>
<td>\leq 0.05</td>
<td>\leq 0.025</td>
</tr>
</tbody>
</table>

Alloying Concept

low carbon content (C \leq 0.09), microalloying with Nb

Carbon Equivalent: \quad CE(iiw) – 0.45 \quad CET – 0.30 \quad Pcm – 0.24
typical microstructure - 32 mm

Quarter plate thickness
Ferrite grain size acc. to
ASTM E112 - Table 2:12-13
Mechanical properties of DILLIMAX 500 ML

Yield strength $R_{p0.2}$ [MPa] and Tensile strength $R_m$ [MPa] for 20 - 50 mm thickness.
Mechanical properties of DILLIMAX 500 ML

51 - 80 mm thickness
Mechanical properties of DILLIMAX 500 ML

Yield to Tensile Ratio $R_{p0.2}/R_m$

Elongation $A_5$ [%]

20 - 50 mm thickness
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High Strength steels in Hydropower

Toughness level of DILLIMAX 500 ML

12 - 50 mm thickness

High resistance against brittle fracture

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MW: 244.3 J
1s: 51.5 J
n: 145
Min: 125 J
Max: 353 J
High resistance against brittle fracture

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Welding: Toughness in HAZ

Charpy-V energy $A_v$ at -40°C [J]

Heat input $Q$ [kJ/mm]

- Fusion line
- FL + 2 mm
- FL + 5 mm

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Calculation example based on S355 in 40mm thickness

Basic tensile properties up to 40mm plate thickness as per standard or data sheet:

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_{eh}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2</td>
<td>345</td>
<td>470 to 630</td>
</tr>
<tr>
<td>S460M</td>
<td>440</td>
<td>540 to 720</td>
</tr>
<tr>
<td>DILLIMAX 500 ML</td>
<td>490</td>
<td>610 to 750</td>
</tr>
<tr>
<td>S500Q</td>
<td>500</td>
<td>590 to 770</td>
</tr>
<tr>
<td>S550Q</td>
<td>550</td>
<td>640 to 820</td>
</tr>
<tr>
<td>S690Q</td>
<td>690</td>
<td>770 to 940</td>
</tr>
</tbody>
</table>

Calculating design values:
1) minimum of $R_{eh}$ and $0.7 \times R_m$
2) minimum of $R_{eh}$ and $0.8 \times R_m$
Design values calculated as minimum of $R_{eh}$ and $0.7 \times R_m$

![Graph showing yield strength vs design value for different grades of steel: S355J2, S460M, Dillimax 500 ML, S500Q, S550Q, S690Q. The graph compares the unused potential (red) with the design value (blue).](image)
Design values calculated as minimum of $R_{eh}$ and $0.8 \times R_m$
High plate thickness / Welding done under severe conditions
Lang Tan Laxiwa Hydro (China)

6 x 700 MW hydropower plant
Location: Yellow River
Delivery: about 4,750 t
Grades: S550QL, S500M, DILLIMAX 500 ML
Thickness: 25 - 190 mm
Yixing (China)

4 x 250 MW Francis turbines for pump
Delivery: 220 t
Grades: DILLIMAX 500M
Thickness: up to 100 mm with Z-properties
Application: bifurcations
Hydro Power Plant Kárahnjúkar, Island

Head: 420 m
Power: 690 Megawatt
Plate thickness: bis zu 150 mm
DH-delivery: 5,330 t
Steel grade: S355ML, S420ML, S460ML, S690QL1
Mayflower TIV I

Jack-up installation for offshore-windmills
Delivery: 5,300 t
Grades: DILLIMAX 500M
Thickness: up to 150 mm
(over 75 mm in Q+T)
Conclusion

- the definition of high strength steel is time dependant
- each hydropower project is individual
- a wide variety of steel grades is needed
- different requirements call for different steel solutions
- DH can offer a wide range of solutions
- individual steel design should be discussed
- out of the many possible grades especially high strength TM processed steels show special benefits
- safe welding can be performed in a big working range