Nb-Microalloyed Steels for Wind Tower Applications

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Nb-Microalloyed Steels for Wind Tower Applications

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Nb-Microalloyed Steels for Wind Tower Applications

In North America, steel plates for wind turbine towers are commonly ordered to one of the following specifications:

- ASTM A572/A709 Grade 50
- EN 10025-2 Grade S355

Chemical Requirements (max. wt. %)

<table>
<thead>
<tr>
<th>Specification</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni+Cr+Mo</th>
<th>Nb</th>
<th>V</th>
<th>CE¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A572-50 &amp; A709-50</td>
<td>0.23</td>
<td>1.60</td>
<td>0.04</td>
<td>0.05</td>
<td>0.40</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>EN 10025-2 S355K2</td>
<td>0.23</td>
<td>1.70</td>
<td>0.035</td>
<td>0.035</td>
<td>0.60</td>
<td>0.60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.45</td>
</tr>
</tbody>
</table>

¹ CE = C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15
Steel plates for wind turbine towers that are ordered to EN 10025-2 Grade S355 with low-temperature CVN requirements also often specify the “normalized rolled” condition (+N delivery condition):

“7.3.1.2 For products ordered and supplied in the normalized or normalized rolled condition (see 6.3) the mechanical properties shall [be met] in the normalized or normalized rolled condition as well as after normalizing by heat treatment after delivery.”
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SSAB Americas’ experience has been that low-carbon Nb- or V-microalloyed grades do not consistently meet the 50 ksi minimum YS requirement in the normalized condition:

Normalizing has a minimal effect on UTS, but results in a drop in YS of about 10 to 20 ksi. This forces the use of higher-carbon grades to meet normalized rolled requirements.
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Program Objective

Highlight the advantages of \textit{low-carbon} microalloyed steels in wind tower applications by comparing the base-metal properties of steels produced through different approaches, including

- controlled rolling (as-rolled \textit{low} C-Nb steel)
- normalized rolling (as-rolled \textit{medium} C-Nb steel)
- furnace normalizing (\textit{medium} C-Nb steel)

This evaluation includes

- microstructure
- internal cleanliness
- tensile properties
- impact toughness
- fracture toughness
- fatigue

\text{data is scarce}
Steels Investigated
Chemical Composition & Carbon Equivalent (wt. %)

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>Ni+Cr +Mo</th>
<th>Nb</th>
<th>CE¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low C-Nb</td>
<td>0.06</td>
<td>1.27</td>
<td>0.011</td>
<td>0.001</td>
<td>0.34</td>
<td>0.27</td>
<td>0.41</td>
<td>0.031</td>
<td>0.35</td>
</tr>
<tr>
<td>Medium C-Nb</td>
<td>0.15</td>
<td>1.39</td>
<td>0.012</td>
<td>0.003</td>
<td>0.22</td>
<td>0.20</td>
<td>0.32</td>
<td>0.019</td>
<td>0.43</td>
</tr>
<tr>
<td>Medium C-Nb Norm</td>
<td>0.15</td>
<td>1.32</td>
<td>0.011</td>
<td>0.003</td>
<td>0.21</td>
<td>0.22</td>
<td>0.23</td>
<td>0.014</td>
<td>0.42</td>
</tr>
</tbody>
</table>

¹CE = C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15

Processing (SSAB Alabama)

• Fine grain practice with low S and Ca treatment for inclusion shape control.
• Cast slabs 6 inches in thickness were reheated to a temperature high enough to dissolve all Nb and rolled to final plate thicknesses of about 0.75 inches.
• Rolling temperatures for the as-rolled steels were controlled to ensure a microstructure of fine polygonal ferrite grains and pearlite.
Although weldability was not investigated as part of this program, the Low C-Nb steel is expected to have better weldability than the Medium C-Nb steels.
Mechanical Testing

• Tensile (SSAB)
  ➢ Full-thickness rectangular specimens
  ➢ T & L orientations
  ➢ ASTM E8

• Impact toughness (Charpy) (SSAB)
  ➢ 1/4t location
  ➢ T & L orientations
  ➢ 72 to -100°F
  ➢ ASTM E23

• Fracture toughness (IIT)
  ➢ Compact specimen
  ➢ Full thickness
  ➢ T-L orientation
  ➢ Fatigue precracked with R = 0.1
  ➢ ASTM E1820

• Uniaxial fatigue (IIT)
  ➢ Hourglass specimen, 0.3” dia.
  ➢ 1/2t location
  ➢ T orientation
  ➢ Smooth surface
  ➢ ASTM E466
Fatigue Testing

- MTS 880 testing machine
- Fully reversed loading ($R = -1$)
- $S_a$ of 30 to 54 ksi
- 4 Hz frequency
  - 8 or 10 Hz near $S_e$
- Test to failure or $10^7$ cycles
- Fan used to minimize adiabatic heating
- Fatigue crack initiation consistently occurred at the specimen surface, and was followed by ductile crack propagation.
RESULTS
Microstructure – 2% Nital Etch

Low C-Nb
- Polygonal ferrite + pearlite
- ~7% pearlite; some banding
- Ferrite grain size ~7.2 μm

Med C-Nb
- Polygonal ferrite + pearlite
- ~28% pearlite; banded
- Ferrite grain size ~6.7 μm

Med C-Nb Norm
- Polygonal ferrite + pearlite
- ~27% pearlite; banded
- Ferrite grain size ~7.4 μm

Internal Cleanliness
- Overall, the internal cleanliness of each steel is good.
- The Low C-Nb steel with 0.001% S is essentially free of MnS inclusions (Type A), while some thin MnS inclusions are present in the 0.003% S Medium C-Nb steels.
- Some oxide stringers (Type B) were detected in the Low C-Nb steel.
- Each steel contains a dispersion of small, spheroidal Ca-Al oxysulfide inclusions (Type D Globular).
The Low C-Nb also appears to contain fewer intergranular carbide particles.
## Tensile and -60°F CVN Properties

<table>
<thead>
<tr>
<th>Steel</th>
<th>Orientation</th>
<th>YS (ksi)</th>
<th>UTS (ksi)</th>
<th>Elongation in 8&quot; (%)</th>
<th>CVN @ -60°F (ft-lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low C – Nb</td>
<td>L</td>
<td>63</td>
<td>75</td>
<td>30</td>
<td>283 (^1)</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>65</td>
<td>76</td>
<td>28</td>
<td>274 (^1)</td>
</tr>
<tr>
<td>Med C – Nb</td>
<td>L</td>
<td>64</td>
<td>81</td>
<td>22</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>64</td>
<td>83</td>
<td>23</td>
<td>31</td>
</tr>
<tr>
<td>Med C – Nb Normalized</td>
<td>L</td>
<td>56</td>
<td>77</td>
<td>28</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>57</td>
<td>77</td>
<td>28</td>
<td>97</td>
</tr>
<tr>
<td>ASTM A572-50 &amp; A709-50</td>
<td>T</td>
<td>50 min.</td>
<td>65 min.</td>
<td>18 min.</td>
<td>Example customer LCVN reqmtns: 25 min. @ -58°F 40 min. @ -40°F</td>
</tr>
<tr>
<td>EN 10025-2 S355K2 (^2)</td>
<td>T</td>
<td>50 min.</td>
<td>68 - 91</td>
<td>20 min.</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Full-size equivalent (FSE)  
\(^2\) 16 < t \leq 40 \text{ mm}
Charpy Transition Curves (Transverse)

CVN Absorbed Energy, ft-lbs

Test Temperature, °F

Low C-Nb
Med C-Nb
Med C-Nb Norm
Room Temperature Fracture Toughness ($K_{IC}$)

**J vs. $\Delta a$ - Low C-Nb (1)**

Fracture Toughness ($K_{IC}$)

Low C-Nb ~350 - 400 ksi $\sqrt{\text{in.}}$

Med C-Nb ~220 - 250 ksi $\sqrt{\text{in.}}$

Med C-Nb Norm ~215 - 290 ksi $\sqrt{\text{in.}}$
The Low C-Nb steel exhibits an endurance limit of about 44 ksi.
Fatigue – All Steels

Alternating Stress, $S_a$ [ksi] vs. Cycles to Failure, $N_f$

- Low C-Nb Linear Fit
- Low C-Nb DNF
- Med C-Nb Linear Fit
- Med C-Nb DNF
- Med C-Nb Normalized Linear Fit
- Med C-Nb Normalized DNF

- Low C-Nb ($S_e = 44$)
- Med C-Nb ($S_e = 39$)
- Med C-Nb Norm ($S_e = 35$)
Contributions to Yield Strength – Ferrite-Pearlite C-Mn Steels
(Grozier & Bucher)

\[ \text{YS}_{\text{calc}} \text{ (ksi)} = 13.3 + 5.9 \times (\% \text{Mn}) + 10.2 \times (\% \text{Si}) + 0.22 \times (\% \text{Pearlite}) + 2.4 \times (1/\sqrt{d}) \]

\[ \Delta \text{YS}_{\text{Nb(C,N)}} = \text{YS}_{\text{meas}} - \text{YS}_{\text{calc}} \]

*Irvine & Pickering solid-solution coefficients:
Mn: 4.7, Si: 12.2, Cu: 12.2, Ni: 0, Cr: -4.5, Mo: 2.0
Precipitation of Nb(C,N)...

- is a significant YS component for the Low C-Nb steel;
- is a modest YS component for the Med C-Nb steel;
- makes no YS contribution for the Med C-Nb Norm steel.

Can Nb(C,N) precipitates cause cyclic hardening during fatigue testing?
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Conclusion

As compared to medium-carbon steels, controlled-rolled low-carbon Nb-microalloyed steels offer considerable advantages to wind turbine tower producers in the form of

- improved impact and fracture toughness
- Improved fatigue endurance limit

<table>
<thead>
<tr>
<th>Steel</th>
<th>YS (ksi)</th>
<th>UTS (ksi)</th>
<th>-60°F TCVN (ft-lbs)</th>
<th>Upper Shelf TCVN (ft-lbs)</th>
<th>Fracture Toughness, $K_Ic$ (ksi/$\sqrt{\text{in.}}$)</th>
<th>Fatigue Endurance Limit, $S_e$ (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low C–Nb</td>
<td>65</td>
<td>76</td>
<td>270</td>
<td>280</td>
<td>375</td>
<td>44</td>
</tr>
<tr>
<td>Medium C–Nb</td>
<td>64</td>
<td>82</td>
<td>30</td>
<td>120</td>
<td>235</td>
<td>39</td>
</tr>
<tr>
<td>Medium C–Nb Normalized</td>
<td>57</td>
<td>77</td>
<td>80</td>
<td>160</td>
<td>250</td>
<td>35</td>
</tr>
</tbody>
</table>
The toughness benefit is attributed primarily due to the lower pearlite and intergranular carbide content of low-carbon steels.

Precipitation of Nb(C,N) provides a substantial contribution to yield strength in low-carbon steels, and may also improve the fatigue resistance through a cyclic strain hardening mechanism.

Based on these results, the implications of specifying the EN 10025 normalized rolling delivery condition are clear:

The steel chemical composition constraints imposed by the EN 10025 normalized rolling requirement result in wind turbine tower plates with reduced weldability, toughness and fatigue resistance.
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Future Work

- Fracture toughness testing at -40°F
- Fatigue crack-growth behavior
- Welding evaluation
THANK YOU!