Cost and Metallurgical Optimization of Structural Steels for Wind Tower Applications

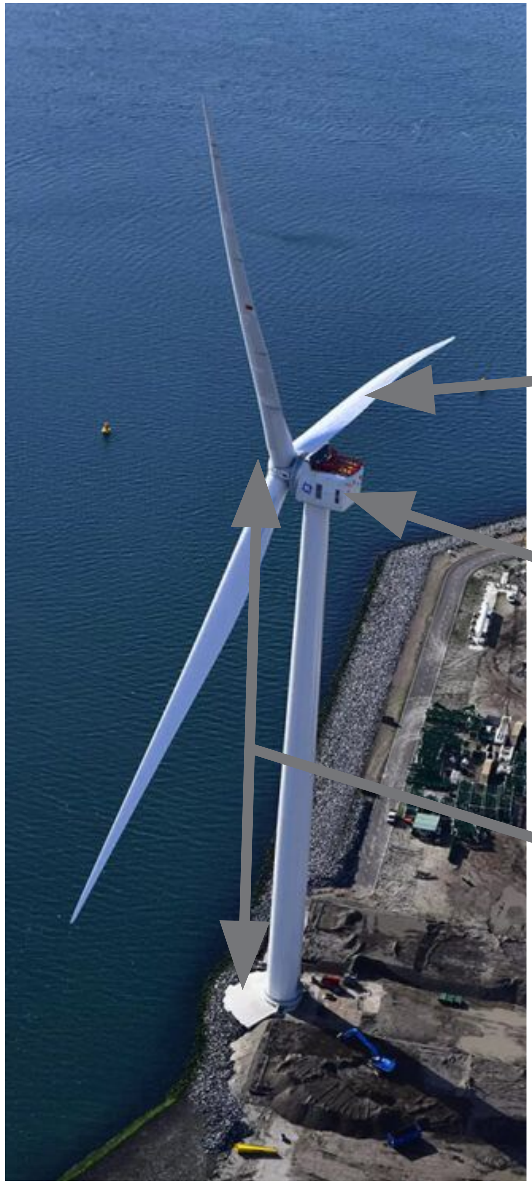
David Jarreta
David Martin
João Paulo Souto
Douglas Stalheim

Contents

Introduction

- Wind power continues to grow as a significant contributor toward the greening of world's energy matrix.
- In the near future, onshore and offshore wind turbines will both supply energy directly to the electricity grid, and power electrolysis systems for the production of green hydrogen and ammonia
- Wind turbine towers are a rapidly expanding and very steel intensive application, consuming large amounts of thick hot rolled plate
- Demand for thick plate for wind towers is driving the adoption of new cost, productivity and performance optimized product concepts

Technology of wind turbines



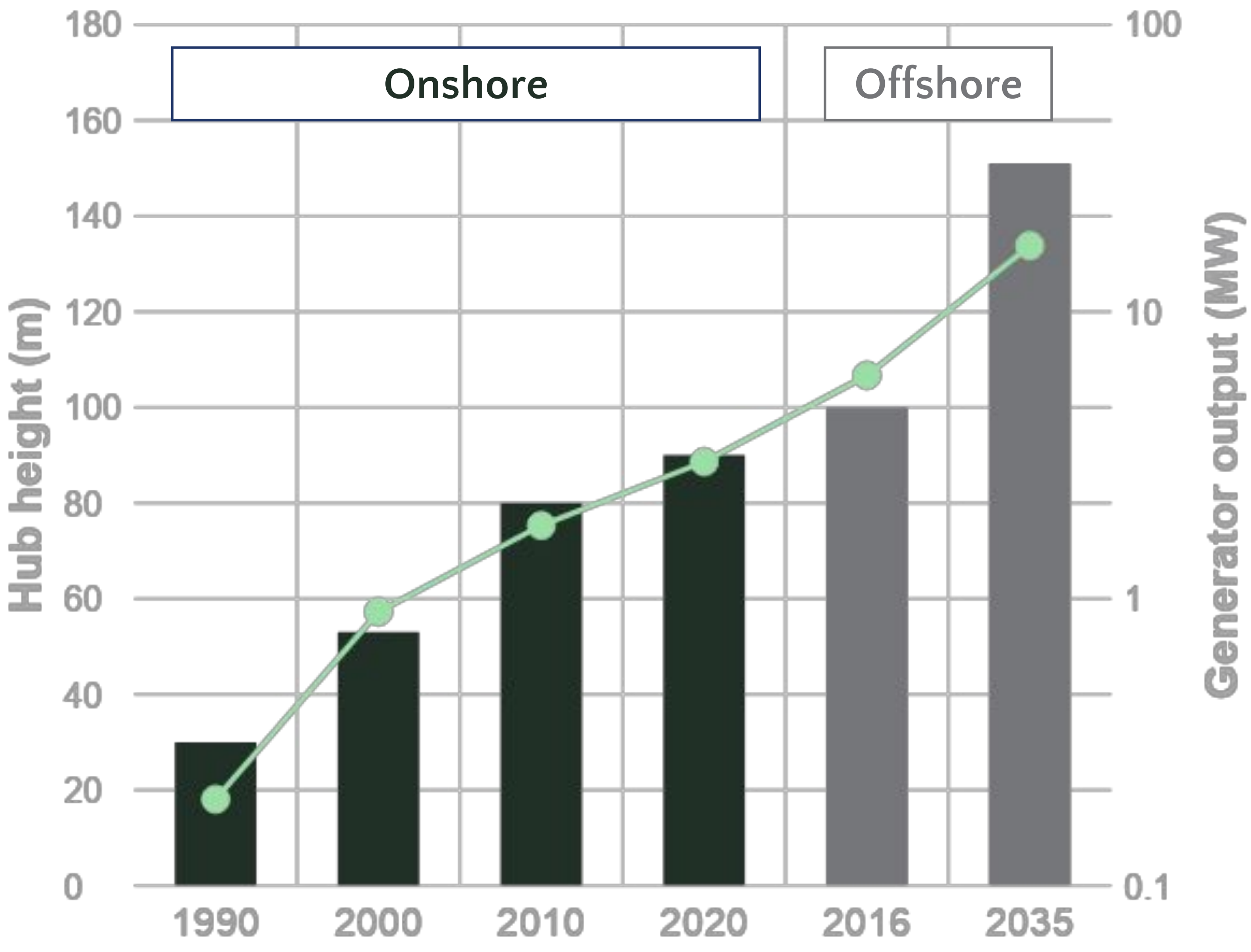
Example: GE Haliade-X 12MW prototype, Port of Rotterdam, 2019

218.2m diameter rotor, **55 tonnes per blade**

Planetary gear set
11m diameter 12MW ring generator,
600 tonnes nacelle weight

150m hub height tower

Evolution of wind turbine sizes



US DOE data shows steady increase in onshore and offshore hub heights and generator capacities since 2010

- Prediction for offshore turbines to reach 160m hub height, 17MW generator capacity by 2035
- Vestas have recently announced a 236m diameter, 15MW prototype turbine for off-shore applications, likely >150m hub height

Evolution of wind turbine sizes

- New turbines are being designed with cut-out windspeeds of $30ms^{-1}$
- Ultra-large turbines are moving into temperate latitudes to exploit higher mean windspeeds
- Production turbine and generator sets over 500 tonnes net weight are entering service
- These large turbine and generator sets and increasingly demanding service environments present significant challenges for tower designs– static load bearing capacity, torsional stiffness, buckling resistance, fracture toughness, fatigue resistance

Use cases for wind tower steels

We identify three steel selection scenarios for modern wind tower applications

1. Cost-effective commodity S355 for smaller hub height applications onshore
2. Offshore and increased hub height applications with strict toughness, fatigue and weldability requirements using thermo-mechanically rolled S355M
3. Reduced weight and high fatigue resistance tower applications using higher yield strength grades such as S420 and S460

Metallurgical Challenges

Regardless of grade type, wind towers present a significant challenge for heavy plate producers

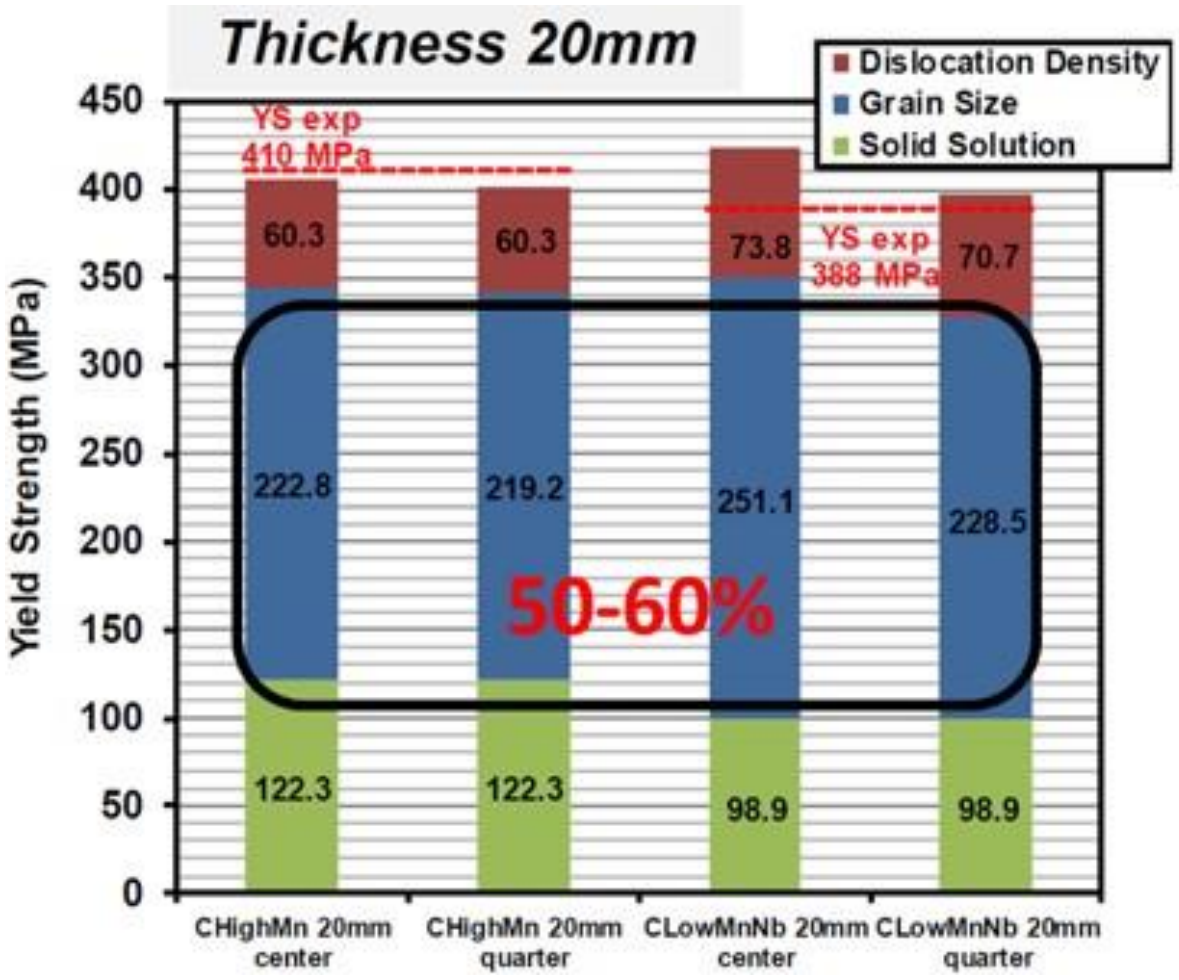
1. How to meet/exceed requirements for mechanical properties and weldability demanded by modern tower designs
2. How select alloy designs which are cost effective with low scope 3 CO_2 emissions
3. How to roll wind tower heavy plates with optimal productivity to meet increasing demand and lower overall production costs

Niobium is a key enabling technology for modern wind tower steel design and processing

Recommended Metallurgical Strategy

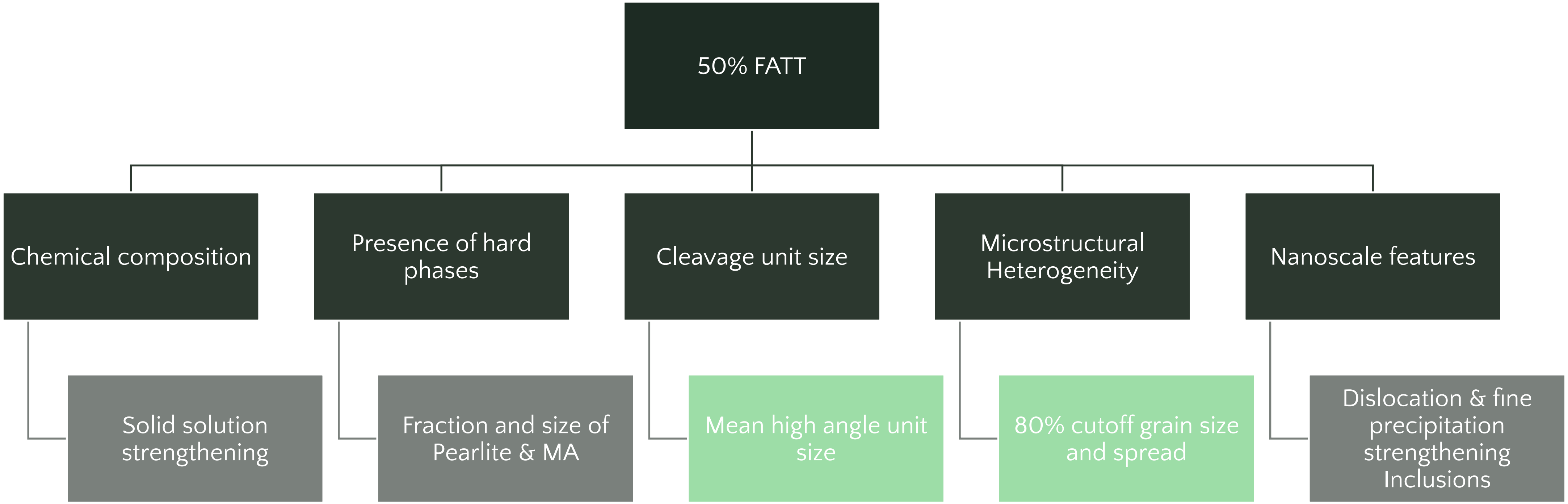
The key to achieve strength, ductility and toughness performance is obtaining a fine, homogenous grain size in the final rolled plate

- 50–60% of strength in commodity S355 is derived from ferrite grain size
- This can rise to 70% in low carbon S420/S460 and line pipe steel grades



Recommended Metallurgical Strategy

Toughness and fatigue performance is strong dictated by the scale and degree of heterogeneity of the rolled plate microstructure



Nb enhanced hot rolling is the recognized solution to reduce grain size, improve homogeneity, and form crystallographic features in structural steels which improve toughness

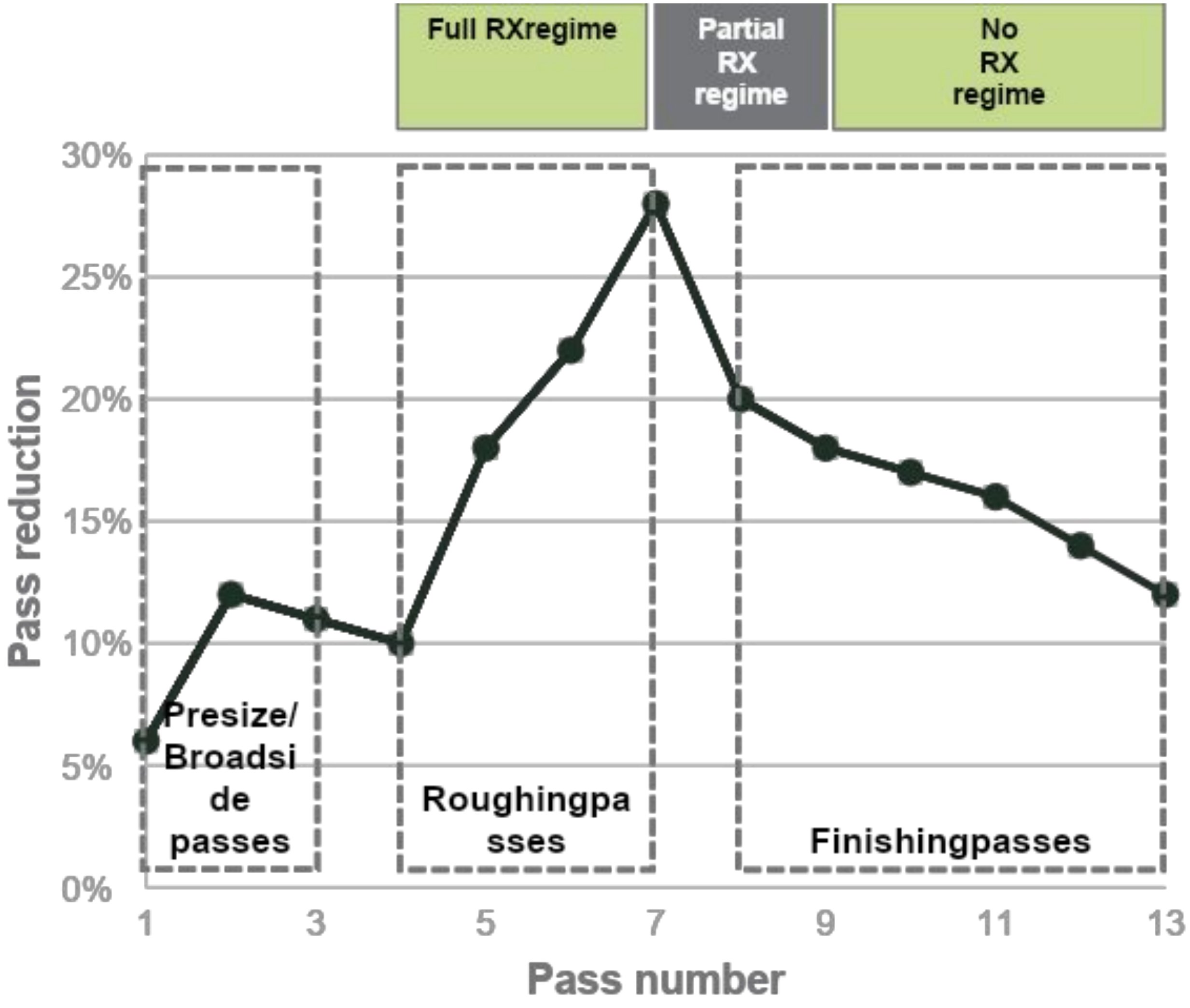
Isasti N, Jorge-Badiola D, Taheri ML, Uranga P. Microstructural features controlling mechanical properties in Nb-Mo microalloyed steels. Part II: Impact toughness. Metallurgical and Materials Transactions A. 2014 Oct;45(11):4972-82.

Recommended Metallurgical Strategy

Yield Strength	Reduction in full static recrystallization regime	Reduction in no recrystallization regime	Reduction in partial recrystallization regime
355-420 MPa	50-60%	< 30%	Minimum possible
420-480 MPa	50-60%	30-60%	

Minimum 27 Joule Charpy toughness requirement	Reduction in full static recrystallization regime	Reduction in no recrystallization regime	Reduction in partial recrystallization regime
0°C	50-60%	10-20%	Minimum possible
-20°C	50-60%	20-40%	
-40°C	50-60%	40-60%	
-60°C	50-60%	60-80%	

Recommended Metallurgical Strategy



- Ideal thickness reduction ratio should be >7:1, excluding broadside passes
- Slabs should be reheated to 1150–1220°C
- A final roughing pass ≥25% reduction is ideal for refining austenite grain size before finishing
- Minimized reduction in partial recrystallization regime

Alloy design philosophy

For producing high volume, cost optimized plate grades we recommend the following alloy design philosophy

1. Select carbon content based on application:
   a) for commodity S355 0.15%C is usually the most economical choice
   b) C content should be reduced towards 0.07%C as strength, low temperature toughness and weldability demands increase
2. Set the Nb content according to the process and toughness requirements:
   a) For commodity S355 and conventional hot rolling processes 0.008-0.015%Nb provides useful austenite grain refinement in reheating and rolling without the need for complex TMCP rolling schedules
   b) For grades with higher low temperature toughness requirements, adjust the Nb content from 0.025-0.06% depending on the amount to no recrystallization rolling reduction required and the mill capabilities

Alloy design philosophy

3. Set substitutional elements (Mn, Si,…) according to solid solution strengthening requirements and mill cooling capabilities to obtain the desired final transformation microstructure and weldability
4. If additional strength is required beyond what can be achieved by optimized rolling and substitutional alloying, then considered precipitation strengthening elements such as Ti and V, noting that their content needs to be matched to the available N content, and that precipitation strengthening typically has a negative effect on fracture toughness.

Example: S355/J0/J2

Objective:
Increase productivity in a conventional controlled rolling + TMCP S355/J0/J2 by adding Nb to existing alloy to increase no recrystallization temperature and use higher finishing mill entry temperature to reduce total rolling time

Grade	Finish rolling start temperature	Total pass time	Tonnes per hour	Conversion Cost per tonne	Nb microalloying cost per tonne
Base 0% Nb	850°C	421s	69	US$84.95	
Base + 0.025%Nb	900°C	340s	85	US$68.61	US$12.61

Final cost saving US$2.64 per tonne, at 16 tonnes per hour higher mill productivity

Conclusions

- Wind energy is key element of the evolving green energy matrix and the expansion of the number and size of future wind power generators is driving strong demand for high performance, cost effective plate steels for wind towers
- We have identified three steel selection scenarios for wind towers, from commodity S355 for smaller hub height, onshore applications, through to lower-C TMCP rolled grades for higher hub height or lighter towers and demanding offshore locations where low temperature toughness and fatigue resistance are critical

Conclusions

- For these wind tower steel grades, we propose a methodology for alloy design which starts from the required strength and toughness requirements, defines the characteristics of the rolling schedule required to obtain those properties
- In this methodology, the Nb level should be set according to mill capabilities and desired degree of no recrystallization rolling and the other elements added to tune phase transformation behaviour and final strength
- In real world examples, Nb based alloy and process optimization has been shown to yield improved product properties, higher plate mill productivity and overall production cost savings for wind tower structural plate steels.

Niobium

Thank you for your attention