Cost and Metallurgical Optimization of Structural Steels for Wind Tower Applications

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Synopsis

Wind continues to expand as an energy source not only for direct electricity generation to the grid, but also to supply electricity to produce green hydrogen. Both wind and green hydrogen have been identified as key energy sources to achieve net zero carbon emissions.

Today, wind-based electricity generation requires support towers produced from thick S355 structural steel with cost effective alloy/processing designs to meet mechanical properties. The push for improvements in generation efficiency in both land and sea based electrical generation requires increasing support tower heights to accommodate larger turbine blades and generators, and this introduces higher toughness and fatigue performance demands for the support tower. Structural steel support towers can be broadly subdivided into three usage scanrios:

1. Standard land-based towers manufactured from cost-effective commodity S355 grade.
2. Offshore and increased height towers that require improved fracture toughness, fatigue, and weldability performance using S355M and similar grades.
3. Thinner wall thickness towers for light weighting and reduced carbon footprint that address both standard land-based conventional towers and offshore/increased height wind tower applications using higher strength S420 and S460 grade.

Regardless of which of the three wind tower application categories a structural steel is destined, alloy design optimization (ADO) coupled with niobium process optimization (NPO) should be implemented to produce the most cost-effective structural steel to meet the mechanical property requirements of the application. Modern alloy designs that utilize the proper carbon and niobium contents can be both cost-effectively produced and metallurgically optimized for the mechanical property demands of next generation support tower designs. This paper summarizes key points and give guidance on how to properly implement alloy design optimization and niobium process optimization to produce cost effective S355, S355M, S420 and S460 structural steel for each of the three categories of wind tower applications.

Keywords: Wind Tower, Cost-efficiency, Strength, Toughness, Fatigue, Weldability, Niobium

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Introduction

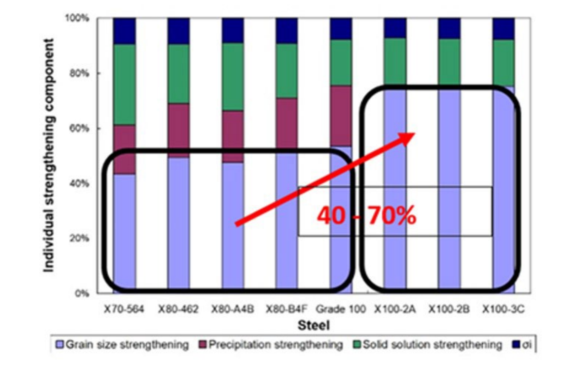
Wind power continues to grow as a significant contributor toward the greening of world's energy matrix. Wind generated electricity can be fed directly into the transmission grid or can be used to generate other energy sources such as gaseous hydrogen through electrolysis. Wind power generators consist of three major technical units: the turbine and blade set which captures wind energy, the generator set which converts rotational energy to electrical energy, and the tower which must support all the static and transient service loads of the combined blade and generator assembly. The height of the tower is determined by the regional wind characteristics and the generator blade lengths. Longer blades can generate up twice as much energy per rotation, greatly increasing efficiency and output. This can translate into tower heights of over 122 m. The largest current turbine and generator sets weigh around 500 metric tonnes, and these can be erected either on land or offshore. The structural steel towers required to support the blade length and weight of this type of modern high-output wind power turbine and generator system can consist of over 70 tonnes of steel per tower (1,2), making this an extremely steel intensive application.

The structural steel used in traditional land-based wind towers has typically been one of the S355 class commodity grades rolled as thick plate. However, as the height and weight of turbines and generators have increased, and locations have gone offshore, there are not only wind frequency fatigue issues, but also ocean wave frequency fatigue potential which must be considered in tower mechanical design and material selection. This has shifted requirements from simple commodity-based grade S355 to TMCP (Thermo-Mechanical Control Processing) rolled S355M or similar grades capable of satisfying the demand for improved ductility, lower temperature fracture toughness, and fatigue performance, with low CE and improved weldability. In addition to these increasing steel grade performance requirements associated with demanding service environments, the increasing weight and height of towers also seen commensurate demand for thicker plates. This demand for higher performance, thicker plates for towers has created new challenges for steel producers to provide cost-optimized structural steel grades which can be produced productively in large volumes. Adding to the structural steel producers' challenge is the push to reduce the carbon footprint of wind towers via light weighting (reducing thickness) by using higher strength grades such as S420(M) and S460(M) with the same enhanced ductility and toughness requirements and lower CE for improved weldability. This light weighting challenge must also be met by producing these higher strength grades in as cost-optimized fashion as possible.

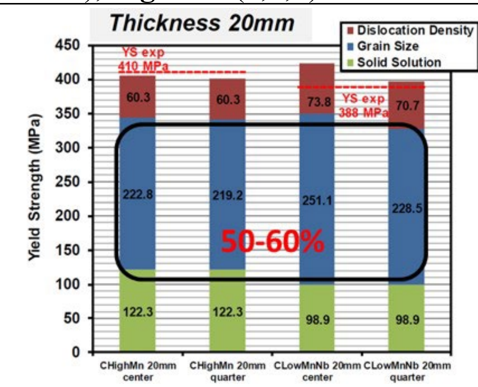
All these wind tower thick plate grade selection scenarios, be they low-cost commodity S355, TMCP rolled high performance S355M, or higher strength grades for light weighting, present a common set of challenges for steel producers – that is how can these grades be produced in ever increasing volumes in the most cost effective and productive fashion with the required mechanical properties, toughness, and weldability. The appropriate use of Niobium microalloying is a key enabling technology for meeting these technical, cost and productivity challenges for wind towers. In this paper we will discuss how a proper understanding and implementation of Niobium alloy design optimization (ADO) coupled with niobium process optimization (NPO) can facilitate cost effective, productive, and high-performance structural steels for modern wind tower applications.

Metallurgical Strategy

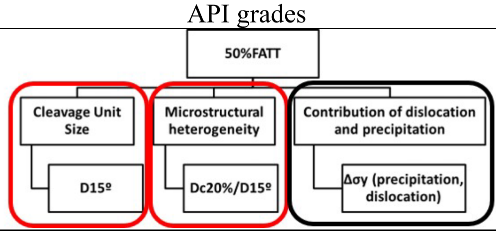
Regardless of which of the three wind tower application classes we have identified, the best steel alloy cost optimization for that class is found through a metallurgical strategy which achieves a proper final through thickness ferrite grain size/homogeneity/microstructural phases for strength, ductility (toughness/fatigue, %RA, elongation), and flatness (residual stress) required for the final plate thickness. The final through thickness ferrite grain size/homogeneity for given microstructural phases contributes 40-70% of the final strength and contribute to the ductile to brittle transition temperature and flatness (residual stresses), **Figure 1** (3,4,5).



Grain size contribution to strength in high strength API grades



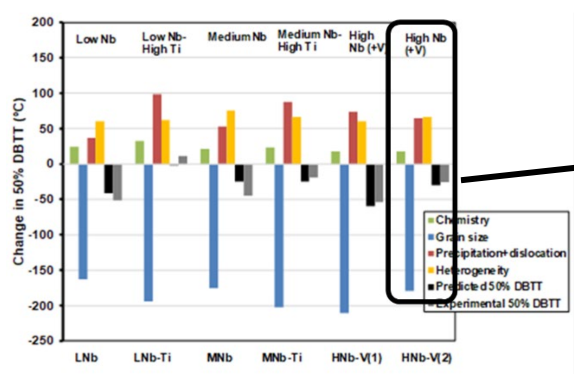
Grain size contribution to strength in commodity S355



Grain size/homogeneity contribution to ductile-brittle transition temperature

$$50\%FATT(^{o}C) = -11Mn + 42Si + 700(Nfree)^{0.5} + 15(\%perl + \%M/A)^{1/3}$$
$$+ 0.5\Delta\sigma_y - 14(D_{mean\_15^{o}})^{-0.5} + 39\left(\frac{Dc20\%}{D_{mean\_15^{o}}}\right)^{0.5} + 23.9(D_{M/A})^{0.5}$$

Detailed metallurgical components contribution to ductile-brittle transition temperature



Example of production structural steel with various alloy designs and evaluation of the contributions from each the ductile to brittle transition temperature

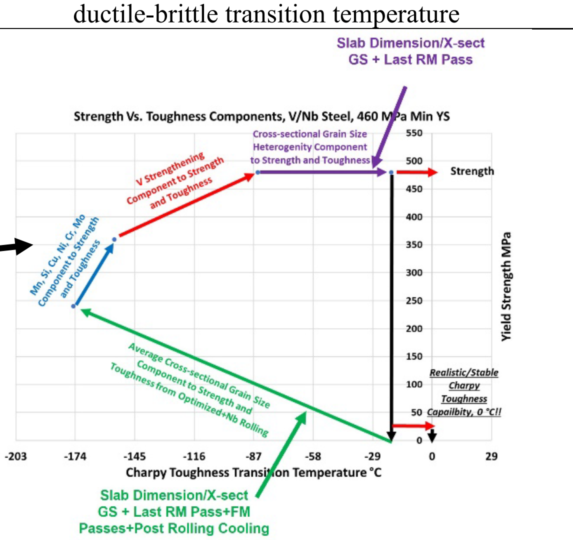


Illustration of various components contribution to strength and transition temperature using the alloy design in the "black box" on the left.

Fig. 1 – Examples of relationships of ferrite grain size/homogeneity to strength and ductile brittle transition temperature in structural steels

Applying the relationships for strength and toughness discussed above to each of these three scenarios identified for potential wind tower applications, we see that as the requirements for each increase in strength, ductile to brittle transition temperature, and plate thickness, the metallurgical strategy target must emphasise producing as fine and homogenous final through thickness microstructure as possible. In addition, with increasing strength and ductile to brittle transition temperature requirements, the desirable microstructural should shift from a traditional polygonal ferrite/pearlite to a lower carbon polygonal ferrite/acicular ferrite with excellent through thickness homogeneity. Charpy V-notch toughness testing can be used to characterize the through thickness homogeneity of the steel being produced by evaluating a toughness transition curve using both average and standard deviation of a minimum of three individual Charpy results for each test temperature. This has been shown to correlate well with quantitative grain size measurements and microstructural and grain size through-thickness homogeneity (6,7,8). Combined with mean flow stress analysis of the actual hot rolling process, these are the two tools used in optimization of both alloy and processing for cost-effective production of structural steels for the various potential end use applications (9,10).

Alloy Design Optimization (ADO) Key Points

The first key component of the production of wind tower structural steels for any of the three possible end use scenarios for optimized cost and metallurgy is implementation of Alloy Design Optimization (ADO). ADO is simply having a proper understanding of the positive and negative contributions of cost and metallurgical response of the key alloying elements used in the production of wind tower steel grades. From a metallurgical point-of-view, the alloying design must contribute to the creation of the desired final phases in the microstructure, and the all-important formation of a fine and homogenous grain size through the plate thickness. The ADO strategy should start with the basic key-approach in order of importance as follows:

1. **Carbon** – utilization of the proper amount, typically starting around 0.15% for commodity S355 and then decreasing through a range down to 0.07% with increasing strength, lower temperature toughness, fatigue and increasing thickness. This means that proper aim carbon that a wind tower steel would use is somewhere between 0.07% to 0.15%. Carbon is a positive for reducing cost but has a negative effect on casting centerline alloy segregation/microstructural banding, ductility and weldability and therefore needs to be used properly in these applications.
2. **Niobium** – Nb in these applications can contribute significantly to a variety of metallurgical attributes in a cost- effective manner. The main contributions that positively effect wind tower steels metallurgy is through grain refinement during reheating and through both solute drag when in lower concentrations of 0.005-0.015% and with higher concentrations up to 0.060% (strength, ductility and thickness driven) through traditional strain induced precipitation in thermomechanical rolling. In addition, solute Nb can positively affect microstructural phase formation, contributing to strength. Utilizing Nb in these various roles, either singly or in combination with other elements, results in optimum cost savings in alloy, productivity, and quality.
3. **Solute Strengthening Elements** – once the C and Nb is properly determined, then solute elements, primarily Mn and Si can be utilized. With the proper use of Nb, Mn can be used in a reduced role as a solute strengthening element (11). This is important for ductility

(toughness/fatigue) performance as Mn contributes negatively to as-cast centerline/microstructural banding along with significant alloy cost implications. Si typically can be used in a 0.10-0.30% with use in a lower range if ductility is of concern. Other solute strengthening elements such as Cu, Ni, Cr and Mo should only be used as needed (due to cost considerations) in higher strength grades or for desirable microstructural phase formation assistance – polygonal ferrite/acicular ferrite (Cr, Mo) or very low temperature toughness performance requirements typically at -40 °C or -60 °C and/or very thick plate (Ni would need to be 0.30% or higher in these applications).

4. **Precipitation Strengthening Elements** – the final consideration in ADO is whether additional strength is needed beyond that provided by grain refinement and solid solution strengthening, in which case precipitation strengthening can be used. Again, precipitating elements should be added in a limited role due to their negative effect on ductile to brittle transition temperature and toughness performance, and higher alloy cost considerations. The most common precipitation strengthening element that is used in this role is Vanadium, but this should be used sparingly if needed, typically in the 0.010% for lower strength thick plate to 0.040% for higher strength S460 wind tower plate. Titanium, on the other hand, doesn't provide a significant precipitation strengthening in plate products. However, Titanium can be used as needed as a high temperature nitride forming element in with a Ti:N ratio in 2.8-3.3 range. In this role, it can work with Nb in controlling slab austenite grain size growth/homogeneity during reheating and in welding.

Typically, any ADO strategy is first implemented utilizing an optimal composition using the existing processing practices (slab reheating, rolling, cooling) in place at the steel plant. Fine tuning of the ADO strategy can be done once initial results are obtained, as required. If additional optimization is needed, be that for plant productivity reasons or enhanced final plate performance, then Niobium Process Optimization (NPO) is the next step for cost and metallurgical optimization.

Niobium Process Optimization (NPO) Key Points

Niobium Process Optimization (NPO) is a suite of modifications to made to slab size selection, reheating, rolling and post rolling cooling strategy, applied either singly or in combination, to further improve the role Nb is contributing to the strength and toughness of rolled wind tower plates. In addition, NPO can be done to optimize the rolling productivity resulting in cost savings (12).

- **Slab Size Selection** – For structural plate steels in wind tower applications, the metallurgical reduction ratio after dimensional rolling passes is completed (so after pre-sizing/broadsiding is complete) and not total reduction ratio is very important to producing a fine/homogenous through thickness microstructure for optimum strength and ductility performance. The optimum metallurgical reduction ratio is ≥7:1 and minimum metallurgical reduction ratio is 3:1. As the metallurgical reduction ratio is reduced from ≥7:1 down to the minimum of 3:1, obtaining excellent ductile-to-brittle temperature and toughness performance becomes more challenging, especially in thicker final plate gauges. **Figure 2** shows examples of metallurgical reduction ratios for a 250 x 2000 mm slab to produce various plate thickness/widths with no presizing + broadsiding and with 10% presizing + broadsiding. Yellow shading is ≤7:1 metallurgical reduction ratio and blue shading is ≤3:1 metallurgical reduction ratio.

250 mm Slab Thickness x2000 mm - Broadside for Width With NO pre-sizing

	2000	250	10	15	21	25	30	35	40	45	60	65	70	75	80	85	90	95	100	125	150
Plate Width		2032	24.61	16.40	11.72	9.84	8.20	7.03	6.15	5.47	4.10	3.79	3.52	3.28	3.08	2.89	2.73	2.59	2.46	1.97	1.64
		2232	22.40	14.93	10.67	8.96	7.47	6.40	5.60	4.98	3.73	3.45	3.20	2.99	2.80	2.64	2.49	2.36	2.24	1.79	1.49
		2432	20.56	13.71	9.79	8.22	6.85	5.87	5.14	4.57	3.43	3.16	2.94	2.74	2.57	2.42	2.28	2.16	2.06	1.64	1.37
		2632	19.00	12.66	9.05	7.60	6.33	5.43	4.75	4.22	3.17	2.92	2.71	2.53	2.37	2.23	2.11	2.00	1.90	1.52	1.27
		2832	17.66	11.77	8.41	7.06	5.89	5.04	4.41	3.92	2.94	2.72	2.52	2.35	2.21	2.08	1.96	1.86	1.77	1.41	1.18
		3032	16.49	10.99	7.85	6.60	5.50	4.71	4.12	3.66	2.75	2.54	2.36	2.20	2.06	1.94	1.83	1.74	1.65	1.32	1.10
		3232	15.47	10.31	7.37	6.19	5.16	4.42	3.87	3.44	2.58	2.38	2.21	2.06	1.93	1.82	1.72	1.63	1.55	1.24	1.03
		3432	14.57	9.71	6.94	5.83	4.86	4.16	3.64	3.24	2.43	2.24	2.08	1.94	1.82	1.71	1.62	1.53	1.46	1.17	0.97
		3632	13.77	9.18	6.56	5.51	4.59	3.93	3.44	3.06	2.29	2.12	1.97	1.84	1.72	1.62	1.53	1.45	1.38	1.10	0.92
		3832	13.05	8.70	6.21	5.22	4.35	3.73	3.26	2.90	2.17	2.01	1.86	1.74	1.63	1.54	1.45	1.37	1.30	1.04	0.87
		4032	12.40	8.27	5.91	4.96	4.13	3.54	3.10	2.76	2.07	1.91	1.77	1.65	1.55	1.46	1.38	1.31	1.24	0.99	0.83

250 mm Slab Thickness x 2000 mm - Broadside for Width With 10% pre-sizing

	2000	250	10	15	21	25	30	35	40	45	60	65	70	75	80	85	90	95	100	125	150
Plate Width		2032	22.11	14.74	10.53	8.84	7.37	6.32	5.53	4.91	3.68	3.40	3.16	2.95	2.76	2.60	2.46	2.33	2.21	1.77	1.47
		2232	19.90	13.27	9.48	7.96	6.63	5.69	4.98	4.42	3.32	3.06	2.84	2.65	2.49	2.34	2.21	2.09	1.99	1.59	1.33
		2432	18.06	12.04	8.60	7.22	6.02	5.16	4.51	4.01	3.01	2.78	2.58	2.41	2.26	2.12	2.01	1.90	1.81	1.44	1.20
		2632	16.50	11.00	7.86	6.60	5.50	4.71	4.12	3.67	2.75	2.54	2.36	2.20	2.06	1.94	1.83	1.74	1.65	1.32	1.10
		2832	15.16	10.10	7.22	6.06	5.05	4.33	3.79	3.37	2.53	2.33	2.17	2.02	1.89	1.78	1.68	1.60	1.52	1.21	1.01
		3032	13.99	9.33	6.66	5.60	4.66	4.00	3.50	3.11	2.33	2.15	2.00	1.87	1.75	1.65	1.55	1.47	1.40	1.12	0.93
		3232	12.97	8.65	6.18	5.19	4.32	3.71	3.24	2.88	2.16	2.00	1.85	1.73	1.62	1.53	1.44	1.37	1.30	1.04	0.86
		3432	12.07	8.05	5.75	4.83	4.02	3.45	3.02	2.68	2.01	1.86	1.72	1.61	1.51	1.42	1.34	1.27	1.21	0.97	0.80
		3632	11.27	7.51	5.37	4.51	3.76	3.22	2.82	2.50	1.88	1.73	1.61	1.50	1.41	1.33	1.25	1.19	1.13	0.90	0.75
		3832	10.55	7.03	5.02	4.22	3.52	3.01	2.64	2.34	1.76	1.62	1.51	1.41	1.32	1.24	1.17	1.11	1.05	0.84	0.70
		4032	9.90	6.60	4.71	3.96	3.30	2.83	2.48	2.20	1.65	1.52	1.41	1.32	1.24	1.16	1.10	1.04	0.99	0.79	0.66

Fig. 2 – Example of metallurgical reduction ratio comparison vs. presizing/broadsiding for a 250x2000 mm slab

- **Reheating** – Slab reheating should be high enough to dissolve Nb precipitates in the as-cast microstructure into solid solution, which will minimize austenite grain size/homogeneity issues, and allow for sufficient roughing mill per pass reductions for control of the through thickness austenite grain size/homogeneity. Typically, the slab reheating temperature will range from 1150 – 1220 °C, depending on final plate thickness, with thicker final plate thickness typically being reheated to lower temperatures for austenite grain size/homogeneity control. In addition, if hot/warm charging is being utilized, it is important to keep the slab core temperature less than the Ac1 temperature, typically 745 °C maximum for wind tower structural steels or there is a risk of austinite grain size/homogeneity issues which will negatively affecting the toughness and ductile to brittle transition temperature performance. Hot/warm charging with surface temperatures of 400-600 °C are used, depending on slab thickness, to maintain a slab core temperature safely below the Ac1 temperature.
- **Hot Rolling** – The simplest NPO hot rolling strategy can consist of the normal mill practices for finishing rolling temperature for the thickness and mill capabilities used to produce commodity S355, or a more controlled strategy with tighter regulation of the finish rolling temperature for improved toughness performance, through to a fully optimized TMCP rolling practice when higher strength and/or further improved ductility performance is required. The exact NPO strategy for selecting the finish rolling temperature is dictated by the Ar3 temperature of the optimized chemical composition. It is important to target a finish rolling temperature at a minimum of 5-15 °C above the Ar3 temperature of the composition, regardless of the post rolling air- or water-cooling strategy. A correctly controlled finishing rolling temperature above the Ar3 temperature provides austenite which will form the through thickness distribution of phases and final ferrite grain size favourable to optimum strength and ductility during post rolling cooling. The two other key hot rolling processing parameters implemented in the NPO strategy are to choose the proper metallurgical transfer thickness, and to optimize key microstructure controlling rolling passes in the rolling pass schedule. The proper metallurgical transfer thickness for optimum austenite recrystallization behaviour (14) should be selected to assure a minimum of 50%, ideally 55%-65% Type I static recrystallization to occur during the roughing phase. This will ensure through thickness austenite grain size evolution/homogeneity prior to moving to the finishing phase. In the finishing phase Type I Static Recrystallization austenite behaviour can continue and/or solute

Nb/strain induced Nb precipitation of the Type II No-recrystallization austenite behaviour can occur along with minimizing any Type III Partial Recrystallization behavior. **Figure 3** shows recommended guidance for recrystallization behaviors for typical structural steel grade used in wind tower applications. Note that when producing heavier gauge wind tower plates, achieving true Type II No-recrystallization behavior can be challenging to achieve, but with proper NPO strategy satisfactory toughness and ductile to brittle transformation properties can be obtained.

Yield Strength Level [Mpa]	Recrystallization Behavior [% of Reduction]		
	Type I	Type II	Type III
≥355, <420	50~60	≥0-30	Minimum
≥420, <483	50~60	≥30~60	Minimum

Min 27J Charpy Toughness Required at [°C]	Recrystallization Behavior [% of Reduction]		
	Type I	Type II	Type III
No Charpy	50~60	≥0	Minimum
0	50~60	10~20	Minimum
-20	50~60	20~40	Minimum
-40	50~60	40~60	Minimum
-60	50~60	60~80	Minimum

Fig. 3 – Recommended guidance for wind tower structural steels recrystallization behaviors for optimum strength and ductility

The second key NPO strategy parameter is to optimize key metallurgical passes in the roughing and finishing phase for through thickness austenite grain size/homogeneity along with final austenite grain size/homogeneity evolution prior to cooling. The last 1-2 roughing passes prior to the transfer thickness and the first 3-4 finishing passes should be at the maximum per pass reduction that the mill can achieve to address the through thickness austenite grain size/homogeneity and Nb solute drag/Nb strain induced precipitation for final austenite grain size/homogeneity evolution prior to cooling. Figure 4 shows two examples of the key roughing/finishing passe for optimum through thickness austenite microstructure formation.

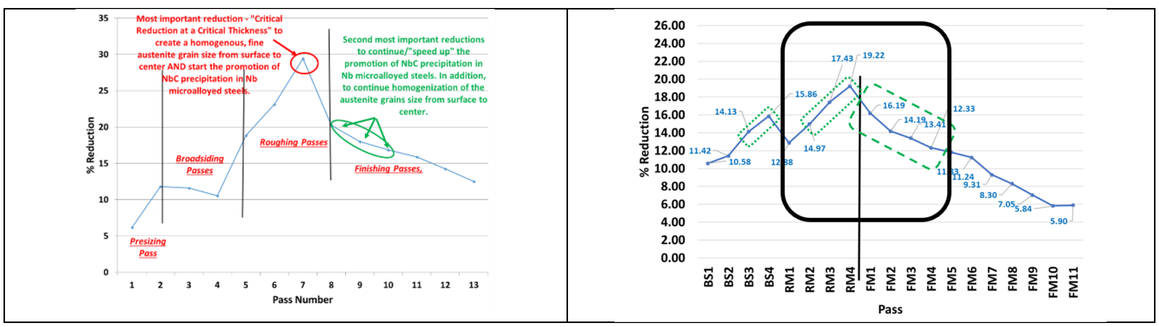
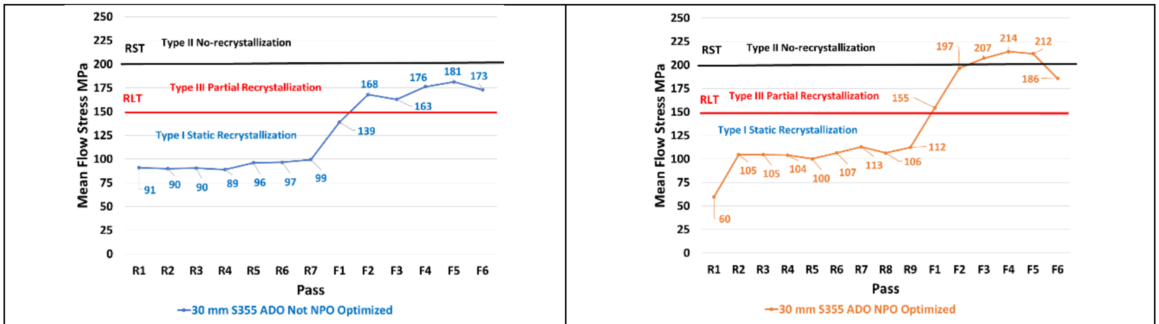
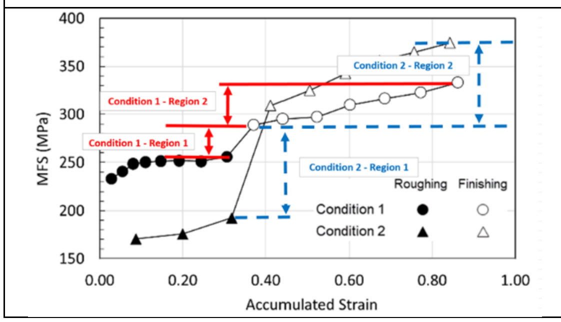


Fig. 4 – Examples of key per pass reductions in roughing and finishing for optimum through thickness microstructure formation.

Mean flow stress (MFS) analysis utilizing the simple modified Sims equation input of actual mill parameters of % reduction, work roll diameter, plate width, and average actual force (13) can identify the effectiveness of the NPO strategy in the through thickness recrystallization behaviors and Nb response. **Figure 5** gives some examples of MFS analysis used with production data to evaluate recrystallization behaviors and Nb performance.





Processing	MFS		
Condition	Region 1	Region 2	Total
Cond. 1	33	77	110
Cond. 2	116	181	297

Fig. 5 – MFS analysis examples of S355, top, and S460, bottom

- **Post Rolling Cooling** – Final post rolling cooling will determine the final through thickness austenite to ferrite grain size and microstructural phases that will form from the rolled austenite during phase transformation. Cooling rate controls the ferrite grain size, and the continuous cooling transformation curve (CCT) will determine the final microstructural phases. **Figure 6** shows examples of the ferrite grain size formation and a typical S355 composition with different Mn/Nb levels and the effect on the CCT and resulting microstructural phase formation with different cooling rates.

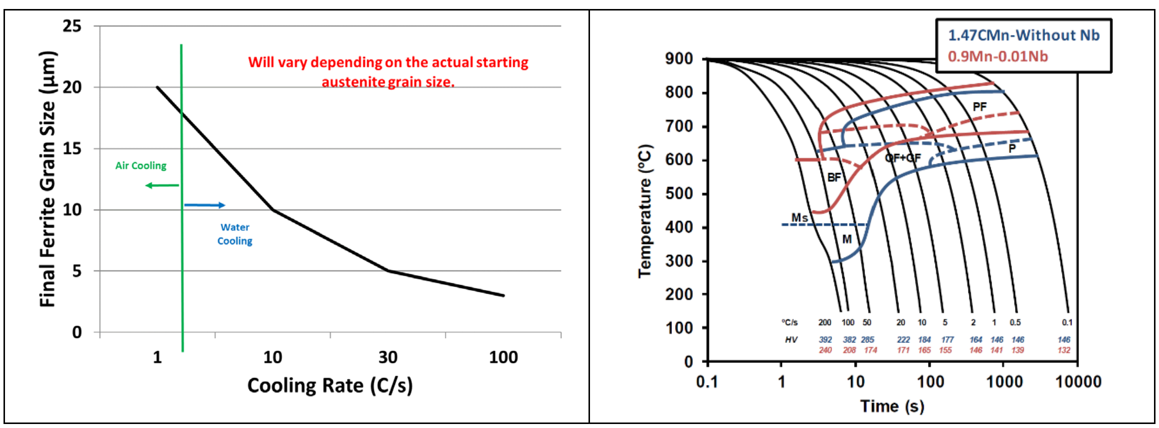


Fig. 6 – Example of post rolling cooling rate on final ferrite grain size formation and microstructural phase formation.

- **Cost Savings** – Proper implementation of NPO can also reduce overall hot rolling production costs by reducing the total rolling time, increasing productivity and the resulting operating cost savings can often outweigh the costs of higher Nb additions. **Figure 7** shows two examples of S355 where cost savings were realized through NPO by increasing plant productivity.

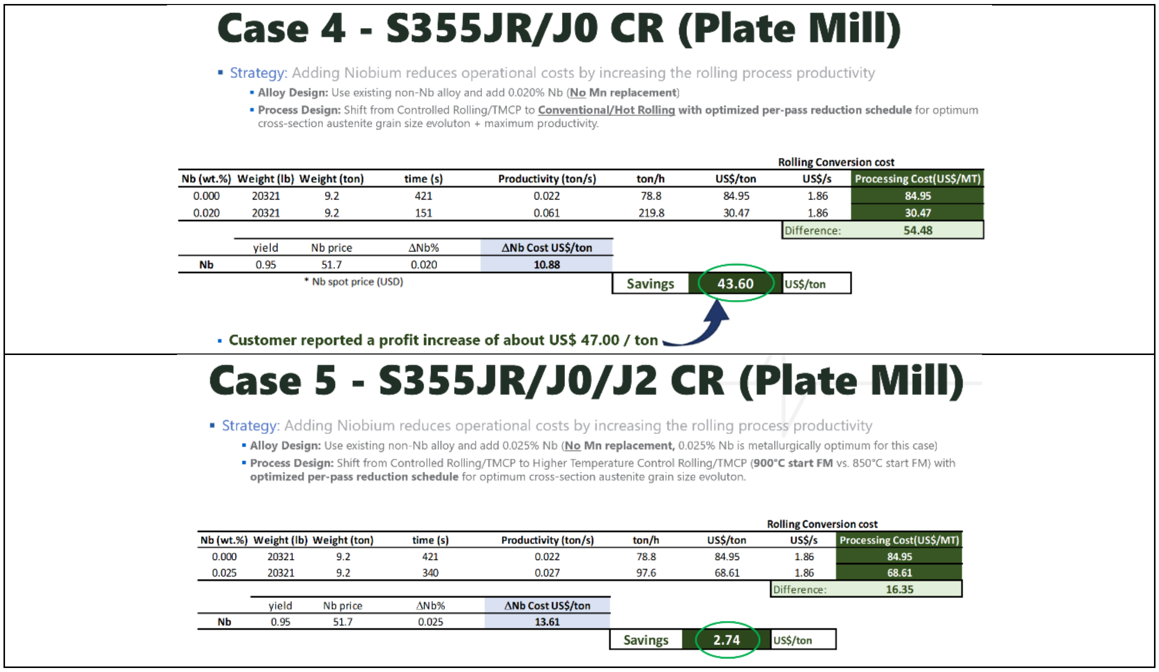


Fig. 7 – Example of NPO cost savings

Conclusions

Rapid growth in the demand for wind energy has increased demand for high performance, cost optimized structural steels for wind towers. We have identified three wind tower use scenarios calling for either S355 commodity grades, S355M high toughness grades for tall towers installed in demanding environments, and light weighting designs using higher strength grades. such as S420 and S460. In this paper we have shown that Niobium microalloying is critical enabling technology for realizing cost and metallurgical optimization in the production of structural steels wind towers in these three scenarios. These can be realized through the proper use of Alloy Design Optimization (ADO) and Niobium Process Optimization (NPO) strategies. The key is to take advantage of the ADO/NPO strategies capabilities to produce as fine and homogenous through thickness microstructure to achieve the desired strength and ductility (fracture and fatigue) properties required for the various wind tower applications. Guidelines and examples of the key points and strategy for both ADO and NPO have been given, demonstrating the critical role that the appropriate use of Niobium microalloying plays in producing cost and performance optimized structural steels for modern land and offshore wind towers.

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