WHITE PAPER

Steelmakers Meet Demand for Taller Wind Towers with Low Carbon Structural Steel Containing Niobium

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KEY TAKEAWAYS

- During the past 15 years, wind turbine towers have increased in height to harvest the more consistent and dependable wind resources at higher altitudes, and to make possible greater rotor diameters for slower blade rotation resulting in more efficient energy output. Wind tower hub heights typically now exceed 100 meters (328 feet) – up from e80 meters (262.5 feet), which had been the previous standard.
- The demand for taller wind towers has increased focus on the use of ferrous metallurgy to strengthen structural supports. Tubular structural dynamics, frequency response, fatigue and fracture toughness – all can be effectively addressed through the use of low carbon structural steel containing niobium (Nb).
- With Nb solutions, steel can maintain an advantage over alternative wind tower materials that include concrete structural plastics and composites. Ferrous steels provide improved fatigue and fracture strength, as well as toughness at low temperatures, and improved weldability for taller turbine installations. Additionally, low carbon Nb-containing structural steel meets the improved mechanical properties architects, civil engineers, fabricators, and designers of wind farms are requiring.
- Unlike traditional steels unable to scale to 100 meters or taller hub heights, Nb-containing steels make possible the production of taller, lighter structural supports with base diameters capable of meeting highway transportation and bridge clearance requirements. Through thinner gauge and lightweight structural support steels, transportation costs and logistic issues can be mitigated.

The new generation of wind turbines are taller, slower, and yield more power. Tower hub heights of 100 meters (328 feet) or higher is the new standard, up from 80 meters (262.5 feet) only 15 years ago.

- Beyond structural supports, MicroNiobium gear steels play a significant role in addressing the reliability and design life of turbine gearboxes, which represent about 25% of wind tower construction costs. According to the U.S. Department of Energy, gearbox failures result in the most downtime per turbine, and contribute to the most costly repairs.
- In addition to wind energy, Nb solutions are on the forefront of other alternative energy developments. The use of niobium oxide to improve electrical conductivity in lithium-ion batteries (LIBs) is linked to faster charging and safety. Other potential applications involve smart windows and perovskite solar cells.

CBMM North America, Inc. can partner with your facility by providing niobium products and value-added steel solutions to help you meet the growing demand for taller wind towers.

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ABSTRACT

Niobium (Nb) has made material science technological advancements for both ferrous and non-ferrous alternative energy applications. Ferrous metallurgical advancements include Nb-containing structure supports for wind towers. The role of Nb in structural steels results in microstructures that provide more robust structural supports with improved strength, fatigue resistance and fracture toughness. The advancement allows for the construction of taller wind towers that improve efficiency. This development in steel was initiated due to the threat of alternative materials derived from concrete, composite graphite and reinforced structural plastics being used. Also, within the wind tower alternative energy sector are MicroNiobium additions being made in gear steels to improve overall performance of the wind tower gearboxes, thereby providing longer service life and reduced maintenance.

The global wind tower market is expected to reach $26 billion by 2023, with a CAGR of 7.45% -- reflective of an increased reliance on renewable energy sources.

Introduction

The global wind tower market is expected to reach an impressive $26 billion (USD) by 2023 with a compound annual growth rate (CAGR) of 7.45%. (1) Segmentation by type and analysis of the wind tower market is divided into tubular plate steel, concrete, hybrid and steel lattice towers. According to market research estimates, the tubular steel towers segment will dominate the other segments with growth envisioned to be driven by cost effectiveness and an ability to provide strength to even taller wind turbine structures. The result is an estimated steel market share of 90% in 2019. Low carbon Nb-containing structural steel applications are meeting several wind tower requirements, including those for improved mechanical properties demanded by architects, civil engineers, designers and fabricators when steel is selected as the material of choice for tower supports. A few years ago, alternative materials such as concrete, structural plastics and composites threatened to replace steel, but today that concern has been temporarily lessened with Nb-containing structural steel as the material of choice. However, steel producers still must be conscious of a materials threat as wind towers are being constructed to taller heights to improve efficiency.

Nb-containing steels also have become an evolving application for wind tower gearboxes. Approximately 85% of today's windmills are equipped with a gearbox. The size of gearboxes has been increasing over the years because of the necessity to improve powertrain efficiency at higher tower elevations. Mechanical property improvements in cyclic fatigue and fracture toughness are being requested by designers. Gearbox repair and maintenance represent one of the highest costs associated with wind tower operation. Also, a change in process technology to high temperature carburization is becoming increasingly more attractive since it can dramatically reduce processing time, improve product performance and increase productivity, thereby reducing gearbox costs. Both mechanical property improvements and high temperature gear carburization are possible with the use of Nb-containing materials.

Global Alternative Energy Background Information

During the past 15 years of wind energy growth, current industry trends have taken tower elevations to 80, 90 and now beyond 100 meters. These towers are being constructed in China, Europe and North America. Turbines have increased in elevation and size, reaching 2.0 MW, 2.5 MW, 3.0 MW and now attaining 4.5 MW. The dead load of these higher elevation structures surpasses 2600 kN (600 kips). Consequently, structural dynamics, frequency response, fatigue and fracture toughness properties of materials, as well as soil-structure interactions, become increasingly important. These towers will need to accommodate larger capacity turbines and rotor blades. The amount of energy available to a wind turbine increases at the cube velocity (V3) of wind speed. With these tougher industry demands, designers and fabricators must consider the current market demographics, including budget constraints, alternative material cost, life cycle performance and supply availability for higher tower construction. Such factors create a huge necessity for cost-effective design and materials relating to construction integration. Low carbon Nb-containing structural steel applications are meeting several of these structural demands for improved mechanical properties demanded by architects, civil engineers, designers and fabricators when steel is selected as the material of choice for tower supports. There have been incidents of concrete tower failures and maintenances issues as heights increase.

The global wind power market remained above 50 GW in 2017, as Europe, India and the offshore sector contributed record years. Chinese installations were down (19.66 GW), but the rest of the world made up most of the difference. Total 2017 installations were 52,492 MW, raising the global total to 539,123 MW. The annual market fell 3.8% compared to 54,642 MW of 2016. The cumulative total was up 11% over the 2016 year-end figure of 487,279 MW. The offshore segment had a record year with installations reaching 4,334 MW, an 87% increase over the 2016 market and bringing the number of total installations to 18,814 MW, a 30% increase in cumulative capacity. Offshore remains about 8% of the global annual market and represents approximately 3.5% of cumulative production. (2)

In March 2017, wind and solar accounted for a record 10% of all US electricity generation. Although the output may not seem significant, it reflects a major achievement for both technologies, which have overcome numerous obstacles to compete with coal, natural gas and nuclear power. This measured growth can be considered the evolutionary stage of the new technological development and can be compared to the shift from traditional telephone landlines to mobile phones in a relatively short timeframe. Renewables obviously still face major barriers. Some are inherent in new technology growth. Others are the result of a skewed regulatory framework and marketplace. (3) The most obvious and widely publicized barrier to renewable energy is cost. Primary contributors are capital expense and the pre-construction phase related to building and installing solar and wind farms. Like most renewables, solar and wind operate at an extremely low cost and maintenance is minimal, thus most of the required capital lies in the installation of the technology.

During 2017, the cost of wind power before tax credits was $30-60 per megawatt hour (MWh) – a measure of energy – and the cost for a large-scale solar operation ranged from $43-53/MWh. Tax credits were designed to further reduce energy bills. By comparison, energy generated by the most efficient natural gas plants costs between $42-78/MWh. Coal power costs were at least $60/MWh. Modern grid technologies, such as advanced batteries, real-time pricing, and smart appliances and windows, will assist solar/wind technologies. Research tests are being conducted in California where consumers are burdened with some of the highest rates of renewable electricity resources in the world. The study is providing real-world validation for the concept that solar and wind can actually enhance grid reliability. A 2017 Department of Energy report (4) cites real-world experience and multiple scientific studies to confirm that the U.S. can safely and reliably operate the electric grid with high levels of renewables. Consequently, there exists a lucrative and potential market for steel in wind towers and niobium oxide containing materials within the alternative energy markets.

Nb-Containing Wind Tower Structural Support Materials

Fatigue and fracture toughness limitations of traditionally higher carbon (exceeding 0.11%C) and V-bearing structural supports initially attracted designers to consider substituting carbon fiber composite and pre-cast concrete towers for wind tower construction at higher elevations. Part of the problem to incorporate such steels was the lack of reliable fatigue and fracture toughness data for currently produced high performance low carbon microalloyed structural steels. With the industry continuing to supply higher carbon structural plate, substrate materials also became attractive to designers. With this situation, an opportunity invited consideration of carbon fiber composite and high performance reinforced concrete substitution for standard HSLA S355 (ASTMA572, EN10025, Q345) structural steel supports. During the same period, CBMM embarked on a project involving several steel mill customers to develop a new Nb-containing steel material design that had been commercialized to halt the threat of alternative materials.

With the proven success of the structural beam technological development and application on a global scale, the Nb-Low Carbon Low Alloy (Nb-LCLA) beam concept was successfully cross-applied and industrially produced as hot rolled wind tower plate. Fatigue and fracture toughness data were generated for Nb-containing steel (5), which provides a viable, cost effective, environmentally friendly solution compared to alternative materials, such as aluminum. The cost benefit and carbon footprint life cycle inventory analysis favor these new Nb-containing structural steel products when compared to alternative structural materials for wind tower construction.

Offshore Wind Towers

The recent application of Nb in high strength offshore wind towers is evolving in Europe, offering possibilities for use in U.S. offshore wind tower projects. Through the optimized addition of Nb as utilized for onshore wind towers, these Nb-containing structural support steels provide fatigue and operational performance in critical wind, wave and oceanic conditions. With the global growth of offshore wind tower construction, alternative energy solutions continue to expand and Nb is playing an increasingly prominent role in these applications.

Construction Plates for Wind Towers

Toughness, fatigue and fracture toughness limitations relating to traditionally higher carbon (>0.11%) structural tower supports have influenced designers to consider alternative materials such as carbon fiber or high performance reinforced concrete. Consequently, with the threat of these alternatives for HSLA S355 structural steel supports, a new steel material design was required. Based on its proven success in beam applications, Nb-LCLA as a hot rolled product provided a viable, cost effective solution. Table I shows the comparison of mechanical properties, namely strength and toughness for low and medium C-Nb or –V for 20 mm plate thickness. (5)

According to the Global Wind Energy Council, the offshore wind power segment had a record year in 2017, with installations reaching 4,334 MW, an 87% increase in cumulative capacity. The first U.S. offshore wind farm was installed in Rhode Island in 2016.

Table I. Mechanical properties of low and medium C plate.

Steel	Orientation	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation in 200mm (%)	CVN@-15 °C (Joules)
Low C-Nb	L	436	514	29.7	384
	T	450	521	28.1	371
Med C-Nb	L	439	561	21.9	103
	T	442	569	23.3	42
Med C-Norm	L	384	528	28.3	243
	T	391	530	27.6	132
Low C-V	L	404	492	25.8	390
	T	404	491	23.9	149
Med C-V	L	394	522	24.5	88
	T	393	523	26.1	33
ASTM A572 & A709-50 min requirement		345	448	18	34@ -12 °C
EN10025-2 S355 min requirement		345	468-627	20	41@ -20 °C

A closer analysis of the upper shelf energy difference between Nb and V is remarkable. A significant difference is exhibited in upper shelf CVN energy performance for the Nb LCLA compared to the low carbon-V wind tower construction plate in both directions. A comparison of low carbon-Nb and low carbon-V wind tower construction plates is shown in Figure 1(a) and 1(b) (5, 6).

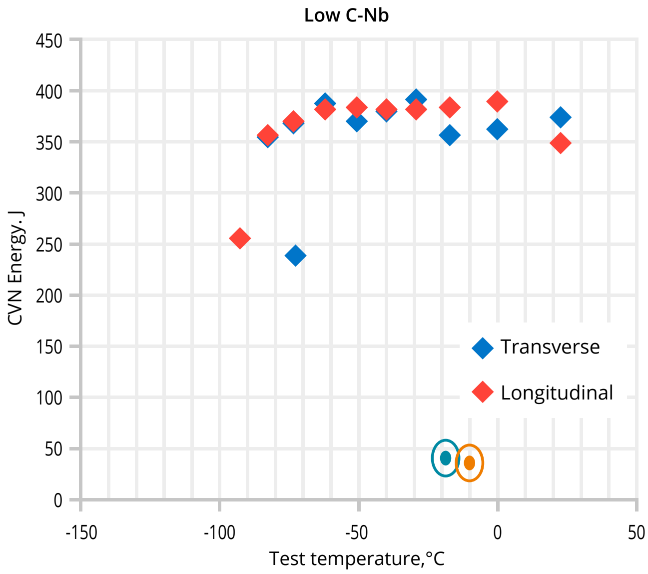


Figure 1. (a) Low C-Nb transverse and longitudinal impact toughness.

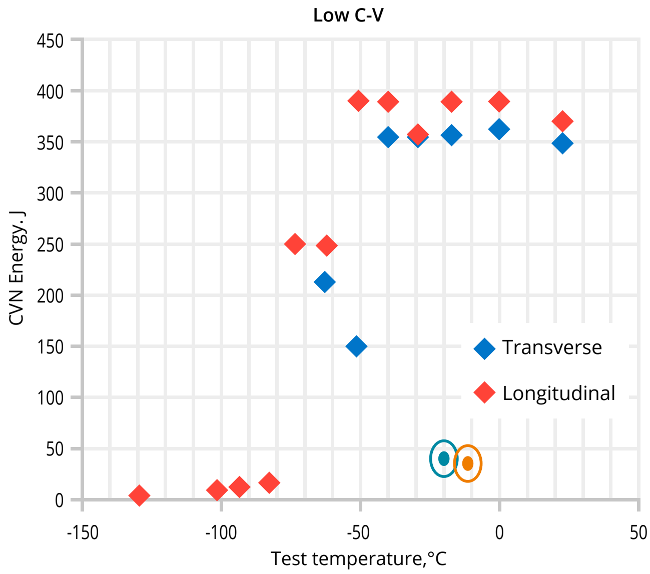


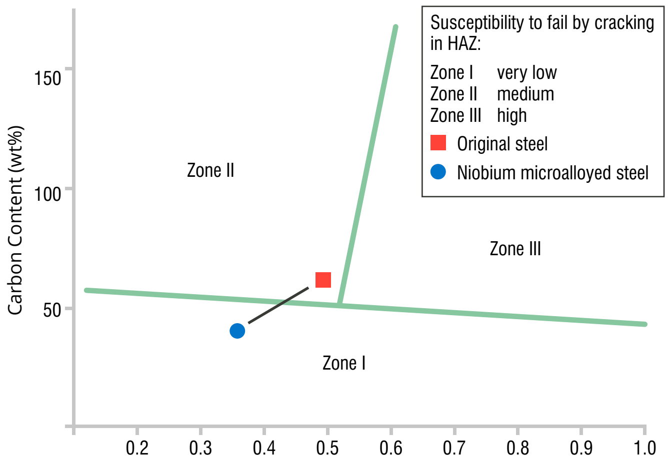
Figure 1. (b) Low C-V transverse and longitudinal impact toughness.

At -65°C test temperature, the CVN energy of the Nb wind tower supports is 400 joules in both directions compared to V wind tower plate, which is only 250 joules in the longitudinal direction and 200 joules in the transverse direction. With the Nb-containing microstructure, the isotropic properties are excellent with 400 joules in both the longitudinal and transverse directions. Based on the superior isotropic Nb-LCLA, fatigue and fracture toughness was measured and appears in Table II. The weldability of these low C-Nb plates also is significantly improved with the move from Zone II for the medium carbon, which requires preheating, into Zone I which requires no preheating as shown in Figure 2.

Table II. Fatigue and fracture toughness comparison (5,6).

	Endurance Limit (MPa)	Fracture Toughness (ksi-in$^{1/2}$)
Low C-Nb	303	375
Med C-Nb	269	235
Med C-Normalized	245	250
Low C-V	245	Invalid test J integral*

** Due to anisotropy and microstructure inhomogeneity.*



$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

Figure 2. Graville diagram. (7)

Concrete Wind Towers

A major research effort has focused on reducing the capital, production and maintenance costs of taller wind turbine towers. Today's turbines often consist of 80 m steel towers. As taller towers become more desirable, material and transportation costs associated with steel tower designs increase significantly. An increase from 80 m (262.5 ft) to 100 m (328 ft) allows turbines to access more favorable wind conditions that exist at higher elevations. (8) Recently, concrete as a construction material has played a role in consideration of its potential for higher wind towers. The demand created by the limitations of current steel tower technologies has led to the development of technologies for precast concrete wind towers possessing a high energy performance capable of overcoming heights and weights that steel towers are unable to achieve. (8)

A major steel limitation is the lack of motivation in steel mills to promote higher strength wind tower plate materials, notably S460. Without motivation to increase wind tower structural steels from S355 to S460, a trend is growing among higher towers exceeding 100 m to use reinforced concrete in various regions of the world. The switch is being driven by the demographics of the geographic region restricting the maximum transport width of steel plate for steel support members of a construction wind farm site. With the increased tower height, the lowest tower segment contains a larger diameter because it is fabricated from a wider plate. Because concrete is durable, this property or concrete plays an important role if wind towers are located in remote areas or in areas with an aggressive environment like that of a marine environment. This change in size also has imposed extremely strict conditions for wind turbine components, including steel towers. In some cases, temporary cement plants are built near the job site.

A new tower concept has been developed using Ultra-High Performance Concrete (UHPC) and other high strength concrete materials that would allow taller wind turbine towers to be easily transported to wind farm sites while adhering to current transportation width limitations. (8) However, by utilizing different combinations of these materials, each design offers unique benefits related to cost, tower weight and connection design among other considerations. The use of concrete as the primary material for large-scale wind turbine towers is a relatively new concept that gained attention because of hub height elevations currently being targeted by turbine manufacturers exploring potential economic benefits. Historically, nearly all erected utility-scale turbines use steel towers, which are transported in three sections and bolted together on site.

Niobium-Microalloyed Steel Solution to Meet Transport Plate Width Restrictions

As tower heights increase, the steel segment comprising the bottom of the tower reaches a point when it is no longer feasible to rely on highway transportation due to width restrictions. The maximum allowable tower base diameter corresponds to an 80 m (262.5 ft) tall tower. However, there is a steel solution for newly constructed taller towers. If higher strength Nb-microalloyed plate were incorporated into the 100 m design, it may be possible to meet the diameter restriction for the tower base. Also, the possibility exists to move to a four segment rather than the current three segment design. The challenges associated with further dividing steel segments have opened the door for concrete solutions to begin taking hold. These concrete designs are addressed for the 100 m limitations currently applied to steel tower construction.
If steel producers and designers consider upgrading towers from the current S275 and S355 grades to some combination of S355, S420 and/or S460MPa design, the lower segment transport plate width restriction would no longer be a problem. Also, the known fatigue and fracture toughness performance is well established for lower elevation towers constructed of Nb-microalloyed steel towers.

Nb-containing steels for the production of taller, lighter structural supports make possible base diameters that can meet transportation clearance requirements and weight loads that can mitigate transportation and logistics costs, effectively securing a steel solution for taller wind tower demand.

Life Cycle Inventory Analysis

A life cycle inventory analysis of steel and steel-reinforced concrete construction reveals that when studying initial equivalent designs at a site, materials design with lower environmental impact positively affects the life cycle assessment (LCA) calculation methodology and assumptions. The expected design life comparison indicates that recycling and the beneficial reuse of steel towers may result in lower annualized environmental impact. One material might be recommended over another due to engineering, aesthetic and/or economic criteria, regardless of overall environmental effects. (9) The traditional criteria for a specific design include engineering requirements, initial and life cycle costs, experience with and availability of a material or technology and aesthetics, as well as the ability to erect the structure based on local environmental conditions, such as climate, topography and transportation logistics. With a comparison of steel and steel-reinforced concrete, the environmental implications of a wind tower material, fabrication and design should be studied on a case-by-case basis.

Factors often ignored in the LCA are dust emissions, water usage, non-hazardous solid waste generation and disposal, generation and disposal of hazardous waste by type, environmental effects of landfills, noise and vibration, and visual impact. If these and other environmental effects are included, assessment results change dramatically and, not surprisingly, yield different conclusions. (9) Data used in such wind tower analyses often contain large uncertainties and reflect past economic and environmental performance. Therefore, a similar assessment using different designs and baseline years may produce different conclusions. Wind towers should be built with material that has comparably the lowest environmental impact and safest, most reliable performance.

Application Status

The application of Low C-Nb wind tower plate is well established, offering enhanced fatigue and fracture toughness properties and isotropic low temperature toughness behavior compared to alternative materials. Consideration of alternative materials, such as concrete, composite graphite and aluminum, has prompted comparisons in many cases to outdated medium carbon structural plate materials. The materials engineering and LCA design should compare the latest high-quality steel materials with alternatives for wind tower construction to ensure an accurate assessment.

Nb-Containing Wind Tower Gearbox Materials

Gear and gearboxes are used for a wide range of applications. For example, high power wind turbines usually have a gearbox transforming the low speed rotor shaft rotation into the higher rotational speed required by the generator. Approximately 85% of today's windmills are equipped with a gearbox. Such equipment is designed as one- or two-stage planetary transmissions. Through the years, gearboxes have gradually become larger due to the upscaling of turbine sizes. In combination with this performance growth, the economic and qualitative optimization of the entire manufacturing chain is of high importance. The gears in wind turbines are sometimes exposed to extremely high loads at the gear flanks and in the root

Turbine gearbox failure is responsible for the most turbine downtime and contributes to the most costly repairs. MicroNiobium gear steels are improving gearbox reliability and design life.

of the gear teeth, for example during sudden changes in wind speed or hard stops. Many wind turbine failures have originated in the gearbox, leading to significant outages and replacement costs. The powertrain of a windmill accounts for approximately 25% of the total equipment cost. In the mining industry, gears and gearboxes can be found in various applications along the entire process chain, including conveyor drives for extraction, mill drive systems in the processing stage, and for the stacker reclaimer and special trucks transportation process. Most gears in these applications also transmit high torque and are often subjected to demanding operating conditions, thereby requiring a long service life. Consequently, large-sized gears are common in many of these products.

Gear failures can be divided into material fatigue-related failures and non-fatigue failure modes, which primarily can be attributed to tribological problems in the lubricated contact, such as scuffing. Tensile strength levels required for spring and gear applications are far greater than those commonly associated with applications involving microalloyed steels. In addition, springs and gears are manufactured using specific high quality metallurgical production processes. The effect of niobium in spring and gear steels are not associated with the precipitation of Nb(CN) carbonitrides inhibition of recrystallization, control of austenitic grain coarsening and precipitation hardening. The interactions of Nb with other elements, as well as slowing down of the austenite to ferrite and carbides transformation are observed in certain cases. (10)

Carburization

The most commonly used gear that steels microalloyed with aluminum (Al) generally is not suited for high temperature carburization due to abnormal grain coarsening. For example, the gear steel 20CrMnTiNb, which is microalloyed with 0.048%Nb and 0.038%Ti, has been compared with the gear steel 20CrMn in terms of the microstructure in the case hardened carburized layer and the core after carburizing at 1000 °C for four hours and mechanical properties after

Table III. Major carburizing steel grades for medium- and large-sized gears in various geographical markets. (10)

Steel Grade	Standard	Alloy Addition in wt %									Region
			C	Si	Mn	P	S	Cr	Mo	Ni	
20MnCr5	EN 10084 (1.7147)	min	0.17	–	1.10	–	–	1.00	–	–	Western Europe
		max	0.22	0.40	1.40	0.035	0.035	1.30			
18CrNiMo7-6	EN 10084 (1.6587)	min	0.15	–	0.50	–	–	1.50	0.25	1.40	
		max	0.21	0.40	0.90	0.025	0.035	1.80	0.35	1.70	
15CrNi6	EN 10084 (1.5919)	min	0.14	–	0.40	–	–	1.40	–	1.40	France, Germany
		max	0.19	0.40	0.60	0.035	0.035	1.70		1.70	
17NiCrMo6-5	EN 10084 (1.6566)	min	0.14	–	0.60	–	–	0.80	0.15	1.20	Italy, France
		max	0.20	0.40	0.90	0.025	0.035	1.10	0.25	1.50	
SAE 8620	SAEJ1249	min	0.18	0.15	0.70	–	–	0.40	0.15	0.40	North Africa
		max	0.23	0.35	0.90	0.030	0.040	0.60	0.25	0.70	
SAE 9310	SAEJ1249	min	0.08	0.15	0.45	–	–	1.00	0.08	3.00	
		max	0.13	0.35	0.65	0.025	0.040	1.40	0.15	3.50	
20CrMnTi	GB T 3077-1999	min	0.17	0.17	0.80	–	–	1.00	0.00	–	China
		max	0.23	0.37	1.10	0.035	0.035	1.30	0.15	0.30	
20CrMnMo	GB T 3077-1999	min	0.17	0.17	0.90	–	–	1.10	0.20	–	
		max	0.23	0.37	1.20	0.025	0.035	1.40	0.30	0.30	
SCM420	JIS	min	0.18	0.15	0.60	–	–	0.90	0.15	–	Japan
		max	0.23	0.35	0.85	0.030	0.030	1.20	0.30		

New product developments within the Nb non-ferrous alternative energy sector are in its infancy (Stage I) of the product life cycle. Laboratory and prototype trials reveal promising opportunities for emerging product applications including the use of niobium oxide in lithium-ion batteries, solar panels, smart windows and piezoelectric.

carburizing and pseudocarburizing. The results indicate that the fine austenite grain exists in the carburized case of 20CrMnTiNb steel while there is abnormal coarsening and duplex grain structure in the case and core of the 20CrMn steel. Average prior austenite grain sizes are 19.5 and 34.2 μm for the steels 20CrMnTiNb and 20MnCr respectively.

The mechanical properties of 20MnCrNbTi steel are superior to those of 20MnCr steel. Specifically, the HV hardness of the 20CrMnTiNb is 40-70 HV higher in the 0.7 mm depth of the carburized layer. Therefore, this steel is suitable for high temperature carburizing whereas the non-Nb-containing steel is not suitable. (10)

Mechanical properties improve with the addition of Nb in rebar, structural shapes and automotive structural components, such as springs. For example, the front suspension coil spring of 0.51%C with Mo-V-Nb for vehicles produced in North America, was developed and commercialized with improved mechanical properties compared to conventional springs. A similar effect was observed when adopting 0.035%Nb in a 9259 engineering alloy spring steel grade. The improved properties are attributed to grain refinement, microstructure, inclusion morphology and precipitate strengthening provided by Nb. (11) The chemistry of the Nb-modified spring steel is shown below in Table IV.

Table IV. Chemistries of modified SAE9259 spring steel.

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	Ti	N	Al
SAE 9259	.61	.86	.014	.021	.78	.008	.008	.51	.008	.005	.002	.003	55ppm	.028
V-9259	.60	.81	.020	.017	.85	.007	.009	.51	.003	.100	.002	-	110ppm	.002
Nb+V+Mo 9259	.51	.69	.016	.020	1.31	.007	.012	.45	.040	.120	.035	-	120ppm	.002

The resultant Nb-V-Mo modified grade exhibited improved yield and tensile strength which translated into improved cyclic fatigue life and improved fracture toughness. The adjusted steel chemistry, grain refinement, Nb-V(CN) precipitation strengthening and overall lower volume fraction of hard oxide inclusions resulted in improved properties. This application illustrates the synergy between Nb and V in these higher carbon engineering tool steels. In actual operation, the Nb to V stoichiometric ratio has been reduced to further lessen the cost of the V and Nb additions. The fracture toughness (KIC) measurements show a 27% improvement in fracture toughness of the Nb+V+Mo modified grade compared to the V-modified grade as shown in Table V.

Table V. SAE9259 dynamic sag after 100,000 fatigue cycles and fracture toughness. (11)

Grade	Dynamic Load (Newtons)	Joule Stress (MPa)	Fracture Toughness K_{IC}
SAE 9259	99.2	957	27.4
V-9259	-	-	29.2
b+V+Mo-9259	72.9	1062	38.2
SAE 5160	-	-	27.4

References

1. Global Wind Tower Market Report (Market Research Future, June 2018).

2. Global Wind Report, Annual Market Update 2017, (Global Wind Energy Council, 2017).

3. "Barriers to Renewable Energy Technologies," Union of Concerned Scientists, Inc., last modified December 20, 2017, https://www.ucsusa.org/clean-energy/renewable-energy/barriers-to-renewable-energy#bf-toc-3

4. U.S. Department of Energy, 2017 Staff Report to the Secretary on Electricity Markets and Reliability, August 2017.

5. Taylor, Keith; Bodnar, Richard; Nelson, Todd; Jansto, Steven; Tsosie, Henrietta; Hu, Zhiyong; Mostovoy, Sheldon and Nash, Philip. "Evaluation of Low and Medium Carbon Nb-Microalloyed Plate Steels for Wind Tower Applications." 2011 International Symposium on the Recent Developments in Plate Steels. Winter Park, Colorado, USA. June 19 – 22, 2011.

6. Garsina, Vladilena, "Fracture Toughness Evaluation of Five Microalloyed Plate Steels for Wind Tower Applications" (master's thesis, Illinois Institute of Technology, May 2015).

7. Graville, B. "Cold Cracking in Welds in HSLA (Microalloyed) Structural Steels." Proceedings of the AIM/ASM Conference, Rome, Italy, November 9-12, 1976.

8. Jansto, Steven G. "Niobium-Containing Wind Tower Structural Steel Comparison to Conventional Steels and Pre-Stressed Concrete." China WindPower Conference. Beijing, China, October 18-21, 2016.

9. Horvath, Arpad. and Hendrickson, Chris. "Steel and Steel Reinforced Concrete Bridges: Environmental Assessment." Journal of Infrastructure Systems. (September 1998): 111-117.

10. Tobie, Thomas; Hippenstiel, Frank; Mohrbacher, Hardy. 2017. "Optimizing Gear Performance by Alloy Modification of Carburizing Steels." Metals 7, no. 10: 415. https://doi.org/10.3390/met7100415

11. Jansto, Steven G. "The MicroNiobium Alloy Approach in Medium and High Carbon Steels: Metallurgy and Applications," Nordic Journal of Metallurgy, no. 7, (2011): 52-58.

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