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Molybdenum in Irons and Steels for Clean and Green Power Generation

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Cover photo: Norris Dam, a hydroelectric dam in East Tennessee (©iStockphoto.com/tankbmb)

Introduction

Electrical energy production is estimated to grow by an average of 2.4% per annum until 2030. About 65% of the world's electric power now comes from fossil fuel combustion [1]. However, governments and international agreements encourage the installation of CO_2-free sources of power. **Figure 1** indicates the total life cycle CO_2 emission per kWh of electrical energy for several primary energy sources. Nuclear, wind, and hydroelectric power have the lowest CO_2 emissions by far. Since the latter two also produce no hazardous waste, they can be considered truly "clean and green" power sources. Yet even for these sources, improvements in life cycle, efficiency, installed cost and cost of ownership are possible. These improvements bring additional reduction in CO_2 emissions. These improvements are inherently connected to the material performance of key components usually made from iron and steel alloys. Performance criteria include strength, toughness, fatigue and wear resistance, formability, and weldability. Molybdenum alloying, combined with appropriate thermomechanical processing, can provide superior material performance. Several examples of molybdenum's beneficial effect on components for wind and hydropower generation equipment are presented here.

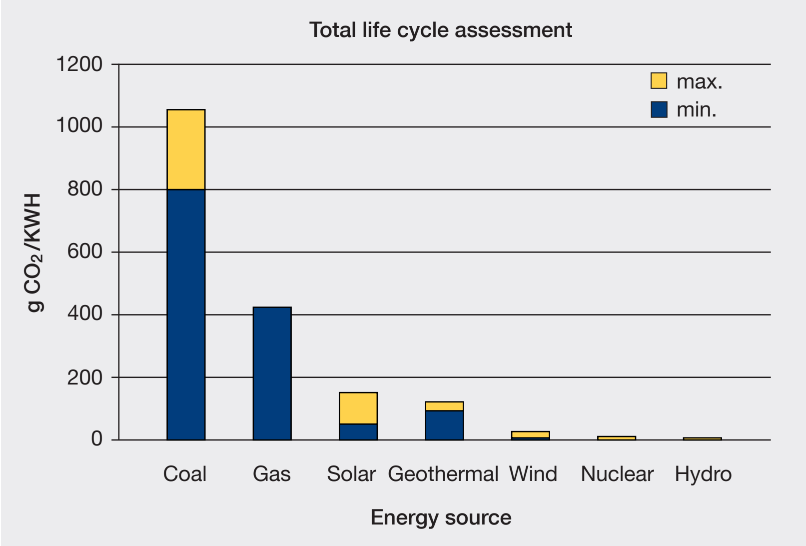

Figure 1. Life cycle CO_2 emissions per kWh of electricity produced using various primary energy sources (source: World Energy Council, 2007).

Hydroelectric Power

Background

Hydroelectric power plants have the highest operating efficiency of all power generation systems. They are largely automated, and their operating costs are relatively low. There are three different types of hydroelectric power plants:

- **Impoundment plants:**
  - Used with high heads (around 200 meters)
  - Very large diameter penstock
- **Pumped storage plants:**
  - Dual action water flow system
  - Used with very high heads (typically 500 up to 1200 meters)
  - Smaller diameter penstock
- **Diversion plants:**
  - Used with low heads and strong current
  - Divert part of river with strong current (no reservoir)
  - Lower capacity than impoundment type

Impoundment hydroelectric power plants store water behind a dam in a natural or artificial lake, and feed the water into the lower-lying power station through a conduit called a penstock. They are the most common type of hydroelectric plant. The head height (the difference between the elevations of the dam and the power station) tends to be moderate, typically between 50 and 200 meters, and the penstock diameter tends to be very large (around 10 meters), allowing high water flow rates. **Table 1** summarizes information about the largest power plants of this type. As an example, each year Itaipú generates 75–77 TWh of electricity, thereby avoiding 67.5 million tons of CO_2 emission. Itaipú operates 20 penstocks, each having a 10.5 meter inner diameter and weighing 883 tons (**Figure 2**). The recently built Karahnjukar hydroelectric power plant in Iceland, while not generating as much power as those listed in the table, operates the two highest vertical penstock lines in the world. They reach 420 meters hight and have an internal diameter of 3.4 meters. The penstock lines and bifurcations are made from fine-grained steel (S355-S420MC) rolled to thicknesses up to 102 mm using controlled thermomechanical processing techniques. Weldability was the most

Table 1. The world's largest impoundment hydroelectric power plants.

Name of facility	Location	Capacity (MW)	Start of operation
Three Gorges	China (Hubei province)	22,500	2008
Itaipú	Brazil, Paraguay	20,000	1983
Guri	Venezuela	10,000	1986
Grand Coulee	USA (Washington state)	6,500	1942
Krasnoyarsk	Russia (Siberia)	6,000	1968
Churchill Falls	Canada (Labrador)	5,430	1971
Bratsk	Russia (Siberia)	4,500	1961

important selection criterion for this steel type. For components subjected to the highest loads, water-quenched and tempered steel (S690QL) in thicknesses ranging up to 150 mm was used.

Pumped storage hydroelectric plants pump water from a lower reservoir to a higher reservoir during periods of low electricity demand. The water is released from the upper reservoir to generate electricity during periods of high demand. The higher the water head, the more compact and environmentally friendly hydropower facilities are. For a given generating capacity, hydropower projects with high water head require smaller dams, smaller waterway systems, smaller diameter penstock and smaller electro-mechanical equipment than those with lower water head. Designers of pure pumped-storage plants typically seek to minimize capital and operating costs either by making hydro turbines more efficient or by increasing the available head to boost rated capacity. Therefore, typical head heights for pumped storage plants tend to be high compared to impoundment

Figure 2. Penstocks of the Itaipú hydroelectric power plant (Brazil/Paraguay).

plants, between 500 and 1200 meters. They also have smaller-diameter penstocks, typically around 3 meters, with thick walls due to the high water pressure.

The parameter H x D (product of the water head and penstock diameter, see **Figure 3**) is one performance indicator for hydroelectric power plants. Increasing diameter (D) and water head (H), which is directly related to pressure, to increase the plant's performance also increases the stress in the penstock walls. This requires thicker penstock walls, and often leads to a decreased reliability of the structure and to complications in manufacturing and assembly. Higher-strength steels allow reduction of the penstock wall thickness, solving both these problems. The most promising steels in hydropower construction are high-strength low alloy (HSLA) steels and, in particular, heat-treated low-alloy steels for the most highly loaded parts of penstocks.

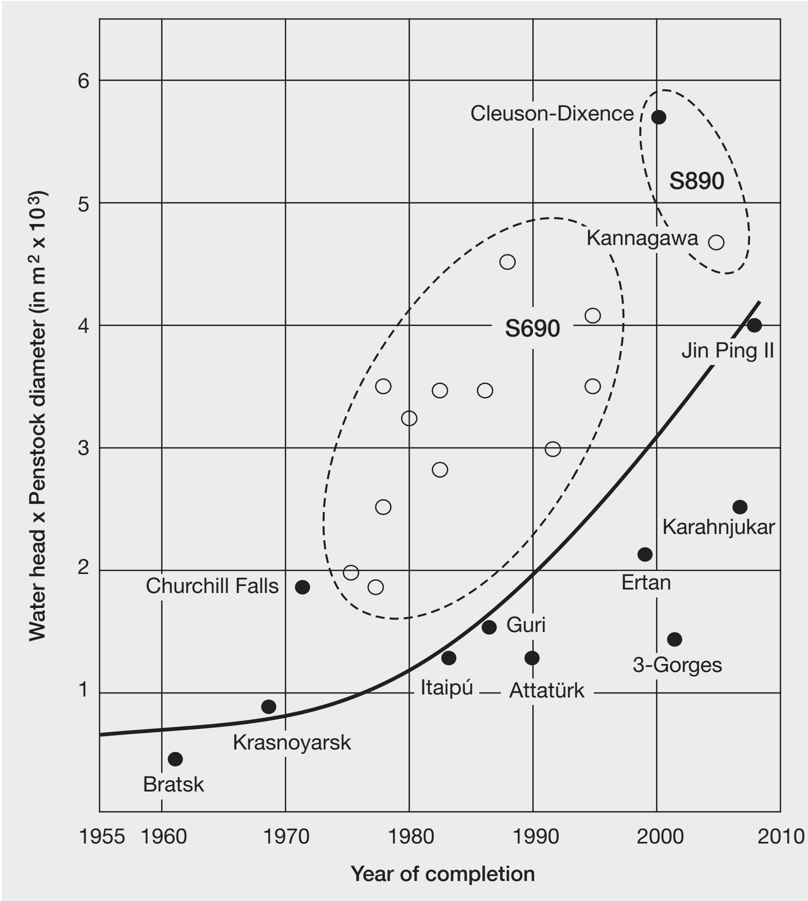

Figure 3. Performance indicator H x D for hydroelectric power plant of impoundment (●) and pumped-storage type (○).

Development of penstock materials

In the 1960's, the steels used in penstocks had yield strengths in the range of 400–500 MPa. From then until the mid-1970's, steels with yield strengths of up to 600 MPa were applied. These high tensile strength steels were used in both conventional hydropower and pumped storage power projects. The S690 steel grade (minimum yield strength of 690 MPa) has been used for penstocks since the mid-1970s, mainly for pumped storage power projects having high water head and therefore high pressure. The high strength steel S890 (minimum yield strength of 890 MPa) was first applied in the 1,200 MW Cleuson-Dixence hydropower project in Switzerland that began operation in July 1998 [2]. Depending on the internal pressure, three different grades of steels were selected. In the upper 1-km section of the penstock, grade P355NL1 is used while the intermediate section uses grade S690QL. The lower section uses grade S890QL (**Table 2**) over a distance of about 3 km, with the plate gauge varying between 20 and 60 mm. A final short section of the same material comprises plate gauges between 60 and 80 mm. The maximum water pressure in the penstock during operation is approximately 200 bar (20.3 MPa).

Using higher strength steel reduces penstock wall thickness and with it total structure weight [3]. **Figure 4** shows the wall thickness reduction achievable by increasing the yield strength of the steel from the standard high strength S355 grade, for designs governed by tensile stress. Reducing the penstock wall thickness also permits a larger internal diameter of the pipe, raising plant efficiency. More importantly, reduced penstock wall thickness and weight lower the cost by reducing material consumption, welding work, and transport and hoisting efforts. In fact, the higher material cost per ton for the higher strength steel is more than compensated by these cost savings (**Figure 5**). Molybdenum alloying becomes relevant in these steel grades for yield strengths above 500 MPa. The need for molybdenum alloying also depends on the plate gauge and the specific production facilities of the steelmaker [4, 5].

Table 2. Chemical composition of S890QL pate grades used for the Cleuson-Dixence penstock.

S890QL	Alloy content (mass%, min./max.)										
	C	Si	Mn	Cr	Mo	Ni	Cu	Nb	Ti	V	Al	B
Supplier A	0.15/0.20	0.25/0.35	0.80/1.10	0.40/0.50	0.50	1.00		0.015	≤0.01	0.05/0.08	0.05/0.10	≤0.002
Supplier B	0.15/0.20	0.20/0.25	1.40	0.20/0.30	0.50			0.025		0.04/0.08	0.05/0.08	≤0.002
Supplier C	0.10/0.15	0.15/0.20	0.80	0.70	0.45	1.30	0.20/0.25	0.015				≤0.001
Supplier D	0.15/0.20	0.25/0.30	0.80	0.60	0.45	1.80						

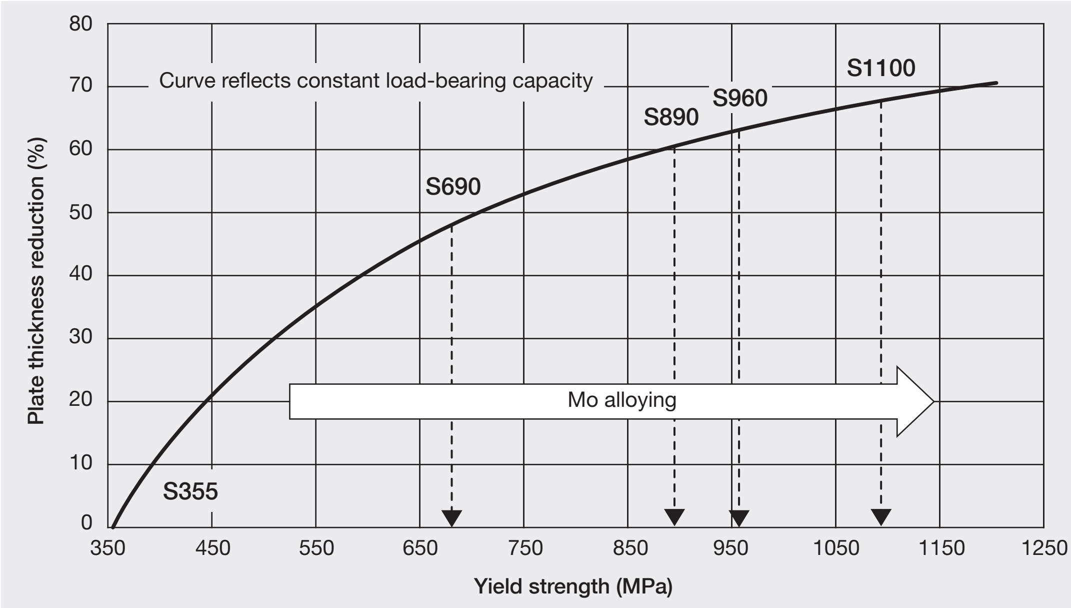

Figure 4. Plate thickness and weight savings potential using ultra-high strength steel grades (YS 690 – 1100 MPa) compared to a standard 355 MPa YS grade, for designs governed by tensile stress.

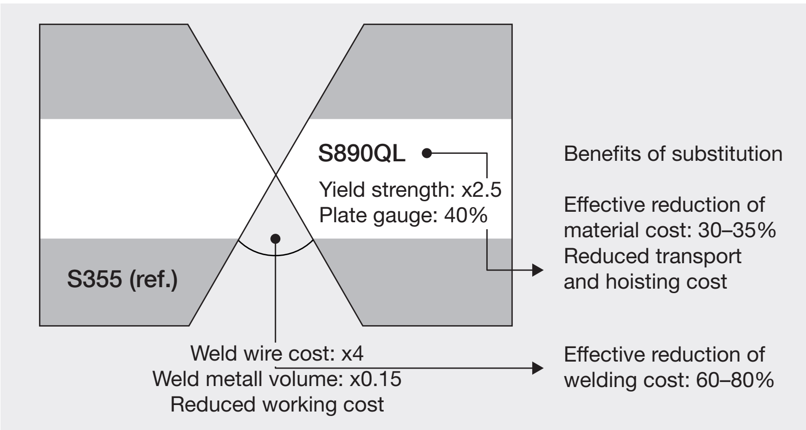

Figure 5. Cost benefits by upgrading penstock material from conventional S355 to S890QL grade, for designs governed by tensile stress.

Weldability of high strength steels

The real concern when shifting to ultra-high strength steel is its weldability. The penstock segments are produced by cold rolling plate to rings and longitudinally welding them in the shop using submerged arc welding (SAW). Single rings, sometimes pre-assembled into a section by circumferential SAW, are transported to the construction site. In front of the tunnel, these single or pre-assembled rings are connected using a SAW process. The pre-assembled parts are then brought into the tunnel and welded to the growing penstock by a coated electrode method (SMAW) or by an automated or semiautomated metal active gas (MAG) process.

The critical nature of weldability is exemplified by an accident that occurred in the Cleuson-Dixence penstock in the year 2000, shortly after it commenced operation [6]. A weld seam in the S890QL section of the penstock fractured over a 9-meter length, causing fatalities, major damage, and a long plant outage while repairs were made. The accident investigation revealed that SAW and SMAW welds are highly susceptible to hydrogen-induced cold cracking in the weld metal, even though the weldability of the base material is satisfactory. Further research revealed that the welds also show sufficient performance, provided proper welding practice (including preheating) is followed. All microstructures – base metal, heat affected zone, SAW weld metal as well as the SMAW weld metal – show the typical tempered martensitic structure.

The most important criterion to judge weldability of a steel grade is the carbon equivalent [4, 7]. Different definitions of this parameter exist, but the most commonly used are the CE(IIW) and the P_{cm} parameters defined as:

$$CE = C + Mn/6 + (Cr+Mo+V)/5 + (Cu+Ni)/15$$
$$P_{cm} = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$$

As the carbon equivalent increases, the steel's weldability decreases. The formulae show that reducing carbon content in steel is the most effective way to improve weldability. Reducing carbon content also improves toughness, but at the same time reduces strength. Therefore, strength must be regained by using other alloying elements and thermomechanical processing during production of the plate material. In order to achieve the required strength without exceeding the maximum specified carbon equivalent, the alloy composition must be optimized with the help of the carbon equivalent weighing factors and combined with the proper thermomechanical treatment.

Table 3. Typical alloying concepts for 25-mm high-strength plate by TM and QT processing.

Grade		Alloy content (mass%)									
	max. gauge	C	Si	Mn	Cr	Mo	Ni	Cu	Nb	V	CE(IIW)
500-TM	35 mm	0.11	0.45	1.65	–	–	–	–	0.050	0.07	0.41
500-QT	70 mm	0.10	0.30	1.40	0.15	0.20	0.60	0.20	0.025	0.05	0.47
690-TM	25 mm	0.08	0.30	1.80	–	0.30	0.50	0.30	0.030	0.05	0.51
690-QT	70 mm	0.13	0.30	0.90	0.40	0.40	1.00	0.25	0.025	0.04	0.53

Thermomechanical treatment and microstructures

The thermomechanical treatments used for heavy plate are rolling + normalizing (N), rolling + quenching + tempering (QT), and thermomechanical rolling (TM) + accelerated cooling (ACC). Of these processes, N-steel has the lowest strength and QT-steel the highest (up to 1160 MPa yield strength). TM-steel in combination with ACC can achieve 690 MPa, and for a specified strength always has a significantly lower carbon equivalent than N- and QT-steels, so the weldability is better. However, the thickness range for TM steels is limited, especially at higher strengths. To obtain sufficient strength and toughness, even in the mid-thickness of heavy penstock plate, requires QT treatment. The chemical composition of heavy QT plate should be designed to obtain a martensitic microstructure at plate mid-thickness upon quenching. The martensite will gain toughness and ductility during subsequent tempering, showing a very favourable combination of properties at the highest strength levels. Molybdenum is one of the most effective alloying elements to achieve this goal.

Unfortunately, martensite can also be formed in any steel during welding if the local cooling rate is high enough. This martensite remains hard and brittle if no postweld treatment tempers it. Untempered martensite is susceptible to cold cracking if its hardness is greater than 350 HV, a value reached at a carbon content as low as 0.05%. The steel grades used in penstocks usually are higher in carbon than that, so special welding processes are required to ensure no untempered martensite exists after welding.

Alternatively, TM+ACC in so-called ultra-low carbon bainitic (ULCB) steel makes it possible to manufacture high-strength steel plates greater than 50 mm thick, with minimum yield strength of 500 MPa [8]. The carbon content in ULCB steels is below 0.05% and Nb (0.05-0.10%), Mo (0.2-0.5%), B, Cr, Ni, and/or Cu are alloyed to achieved a fine-grained, fully bainitic microstructure that provides high strength and good toughness. The maximum hardness of the heat-affected zone (HAZ) is 280 HV or less, even under welding conditions with very rapid cooling such as arc-strike. Welds in these materials have excellent resistance against cold cracking.

However, the mainstream high strength steels for penstock have carbon contents between 0.08 and 0.15%. Representative alloy concepts for 500 and 690 MPa yield strength grades are shown in **Table 3**. TM-steels have a lower CE at the same specified strength than QT-steels. The table also shows that TM-steels are limited in their maximum gauge. In TM-steels, Mo alloying is usually necessary to obtain a yield strength of 550 MPa or more, whereas QT-steels always require Mo alloying. For the latter, the Mo content increases with strength level and plate gauge to a maximum of around 0.7%. Molybdenum not only provides better through-hardening capability during quenching, but also provides good tempering resistance, allowing the strength-toughness combination to be optimized.

Practical consideration during field welding

Figure 6 compares the weldability of several high strength plate grades, showing the material hardness as a function of the cooling time from 800 to 500°C after welding (ΔT8/5) [4, 7]. While the carbon

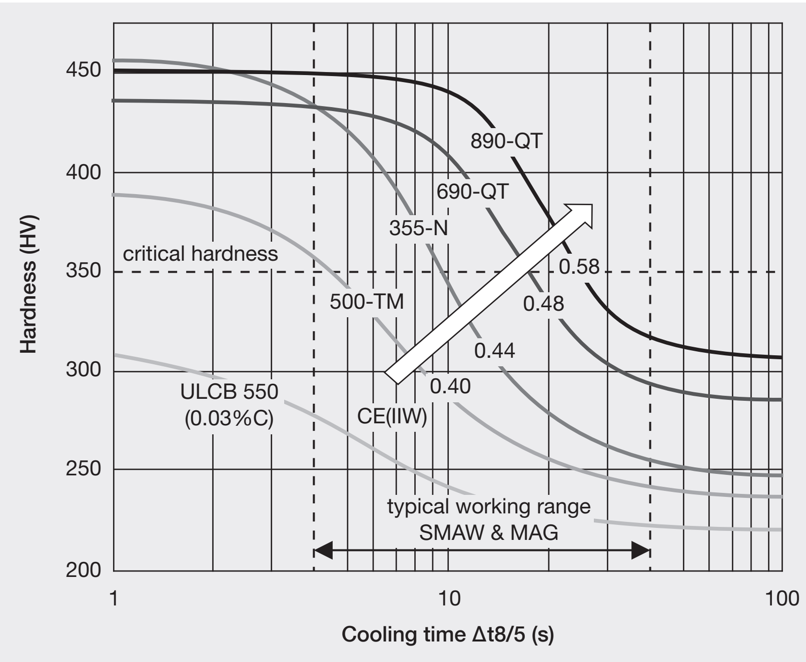

Figure 6. HAZ hardening of various high strength plate grades as a function of cooling rate after welding.

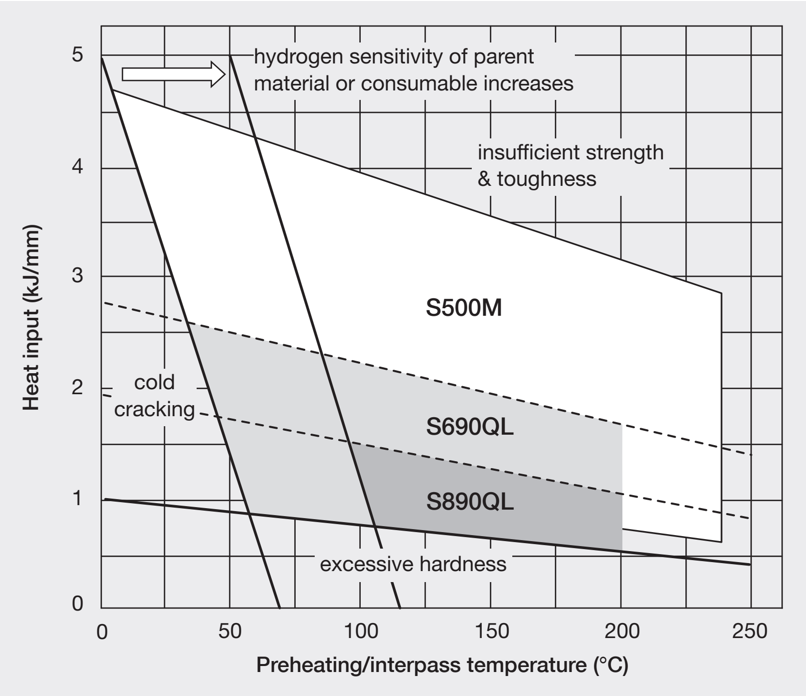

Figure 7. Welding process windows for different high strength plate grades.

content controls the plateau hardness of the martensite at very short cooling time, the CE determines at which cooling time martensite forms. The critical ΔT8/5, the cooling rate at which the hardness remains below 350 HV, is shifted to longer times with increasing CE, and tends to be in the typical working range of SMAW and MAG processes used for on-site welding of penstock sections. Only the 500 MPa TM-steel, with its relatively low CE of 0.40, appears to be uncritical under these cooling conditions. Grades with a higher CE, therefore, demand special precautions for welding, including pre-heating of the weld zone. The process window becomes smaller as the CE rises, i.e. as the strength or the plate gauge increases (**Figure 7**). Welding with too much heat input degrades strength and toughness, whereas too little heat input results in excessive hardness and increased cold cracking susceptibility in the HAZ.

The welding consumables that produce tensile properties overmatching the ones of 690 or 890 MPa QT-steel demand a high alloying content. A combination of 1–2.5% Ni, 0.5–1.5% Cr and about 0.5% Mo is typical for high strength consumables. Because their chemical compositions have high CE values and their microstructures are as-cast, weld metals for such ultra-high strength steels are often more susceptible to hydrogen induced cold cracking than the HAZ of the parent material. In order to avoid weld cracking, preheat and interpass temperature must be adapted to the weld metal. Therefore, a steel with reduced CE does not allow dropping these welding precautions. In other words, high strength steels with reduced CE, as achieved by TM-rolling, need essentially the same welding precautions as the higher alloyed QT steel. However, TM-rolled steels and particularly ULCB steels demand less stringent welding conditions with regard to preheating temperature, range of applicable cooling rates and heat input.

Evolution in alloy design to increase the strength and weldability of steels has brought significant cost and efficiency benefits to hydroelectric plant design and construction. Molybdenum plays an important role in these alloys as moderate additions efficiently help to provide high strength, especially when thick plate gage is required (**Figure 8**). Furthermore, Mo alloying combined with quenching & tempering produces excellent toughness across the entire plate thickness.

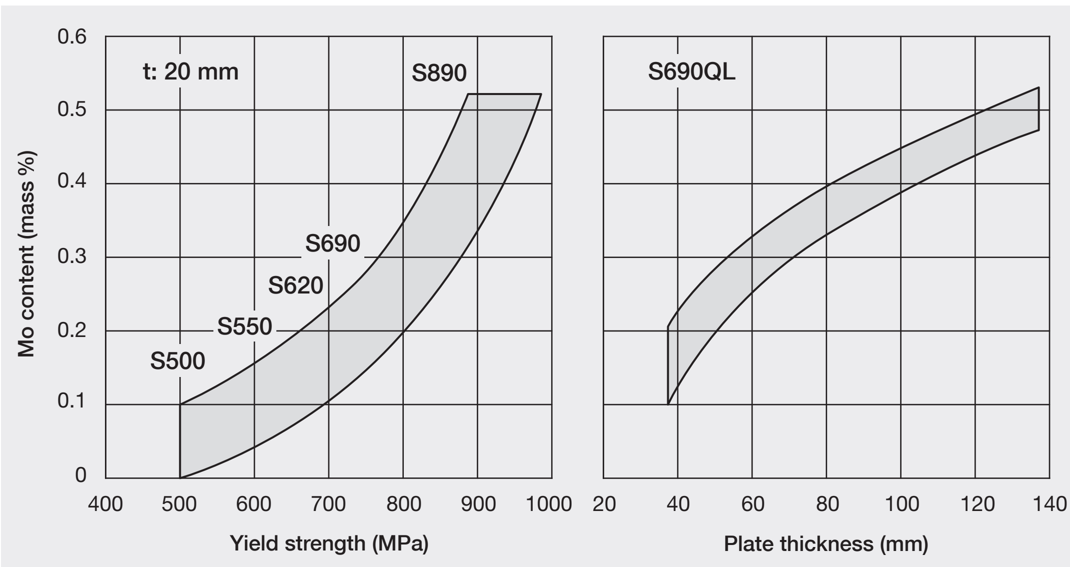

Figure 8. Typical ranges of Mo content in Q&T plate steel depending on strength level (constant plate thickness: 20 mm) and plate thickness (constant yield strength: 690 MPa).

Wind Power

Background

Wind power is a fast growing energy sector, having evolved from a negligible contribution in the early 1990's to a consolidated world production of around 100 GW by the end of 2007 [9]. Forecasts predict a further rapid increase towards 1000 GW by 2020. Utility-scale turbines range in size from 100 kilowatts to as large as several megawatts, with the larger turbines being more efficient and cost-effective. Turbines are grouped together into wind farms (**Figure 9**) that provide bulk power to the electrical grid. These wind farms are increasingly being constructed offshore because land-based sites for wind are becoming scarce, especially in densely populated regions, and wind resources are generally stronger and more dependable off shore. Recent offshore windmills are in the 5 MW class, and future designs are expected to provide even higher performance. Investment, operations, and maintenance costs are roughly 70% higher for offshore windmills as compared to land-based mills. However, offshore plants produce about 50% more energy due to higher wind speeds, so the life cycle cost per MWh becomes competitive with land-based plants.

Measured in tons of material per MW, wind power is the most iron- and steel-intensive of all power generation methods. Existing designs use about 300 metric tons of iron and steel per installed MW. **Table 4** lists the major components in a wind power system, together with their cost. The numbers are for a 2 MW land-based design with 100-meter hub height (**Figure 10**) [10]. In offshore installations, a jacket, pile or tripod foundation anchoring the tower to the sea floor is also needed. It weighs 200 to 700 tons depending on the water depth.

Figure 9. Installation of 5 MW offshore windmills in the Thornton Bank project, Belgium; foreground: jack-up platform with hoisting cranes (courtesy Jan Oelker).

Table 4. Major components of a 2 MW land-based windmill, their relative impact on the total equipment cost and typical materials used.

Component	Cost share	Material	Function / Remarks	Alloy design
Tower	26%	Steel plate	Ranges in height from 40 m to more than 100 m.	HSLA (Nb, V) plate, typically S355 or grade 50.
Gearbox	13%	Steel forgings, cast iron	Gears increase the low rotational speed of the rotor shaft in several stages to the high speed needed to drive the generator.	Carburizing steel, typically 18CrNiMo7-6; Nb, Ti additions for high temperature carburization; Spheroidal cast iron (GJS) or austempered ductile iron, ADI (Mo alloyed).
Transformer	3.5%	Steel sheet	Converts the electricity from the turbine to higher voltage required by the grid.	Electrical sheet (high Si).
Generator	3.4%	Steel forgings	Converts mechanical energy into electrical energy.	Heat-treatable CrNiMo(V) steel.
Main frame	2.8%	Steel plate or cast iron	Must be strong enough to support the entire turbine drive train, but not too heavy.	HSLA (Nb, V) plate, Mo alloying for extra strength; GJS or ADI (Mo alloyed).
Pitch system	2.6%	Steel forgings	Adjusts the angle of the blades to make best use of the prevailing wind.	Heat-treatable CrMo steel.
Main shaft	1.9%	Steel forgings or cast iron	Transfers the rotational force of the rotor to the gearbox.	Heat-treatable CrMo steel; GJS or ADI (Mo alloyed).
Rotor hub	1.4%	Cast iron	Holds the blades in position as they turn.	GJS or ADI (Mo alloyed).
Yaw system	1.3%	Steel forgings	Mechanism that rotates the nacelle to face the changing wind direction.	Heat-treatable CrMo steel.
Brake system	1.3%	Cast iron	Disc brakes bring the turbine to a halt.	GJL
Rotor bearings	1.2%	Steel forgings	Have to withstand the varying forces and loads generated by the wind.	Through-hardening Cr-steel (100Cr6) or CrMo-steel (100CrMo7-3).
Screws, studs	1.1%	Steel bar	Hold the main components in place; must be designed for extreme loads.	Heat-treatable steel, CrMo or CrNiMo type.

Figure 10. Inside of a Nordex N80 (2.5 MW) nacelle showing the power train in colour (courtesy Nordex AG).

Table 5. Weight of major components of a 5 MW land-based windmill and potential for material optimization.

Component	Weight	Improvement potential
Tower	750 t	Reduce plate gauge by upgrading strength from grade 50 to grade 70 or 80 (ksi) → less steel; reduced welding effort during segment fabrication; reduced transport and hoisting weight.
Machine support frame	69 t	Reduce plate gauge by upgrading strength to grade 80 or 100 (ksi) → less steel; reduced welding effort; reduced transport and hoisting weight.
Generator support frame	20 t	
Rotor hub	66 t	Replace standard ductile iron by ADI → reduce weight by up to 50%, increase toughness.
Rotor shaft	27 t	
Gearbox	63 t	Housing: Replace standard ductile iron by ADI → reduce weight up to 50%, increase toughness. Gear: Increase shell hardness and core toughness → reduce gear wear and failure. Increase carburizing temperature by microalloying → reduce treatment time and cost.
Generator	17 t	Increase tempering temperature (enabled by increased Mo addition and Nb microalloying) → optimize combination of strength and toughness.

The wind energy businesses has also a big impact on other steel-intensive industries since large mobile cranes and, in the case of offshore placement, crane barges and jack-up platforms are needed to erect the turbines (**Figure 9**). Because of the hoisting heights and weights involved, crane booms made from ultra-high-strength steel are required. Applicable steel grades are in the range of S690 to S1160 [3]. Crane booms are usually made from quench and tempered plate and require Mo additions of 0.3 to 0.5 percent.

Table 5 indicates the weights of major components in a 5 MW land-based turbine [11]. The nacelle including the rotor weighs more than 400 tons. This weight residing at a height of over 100 meters presents challenges during both construction and operation, as it applies large forces to the supporting tower. With the anticipated increase of power performance, especially for offshore turbines, and the associated increase of component sizes, weight reduction becomes an important issue. In this respect, housings and support frame structures can be reduced in thickness by switching to stronger materials. For the support frames, steel grades can be upgraded according to the principle shown in **Figure 4**, suggesting that a weight reduction of 20 to 40 percent is feasible. Another considerable weight saving opportunity exists for the larger castings such as hub, hollow shaft and gearbox housing currently manufactured from spheroidal cast iron (GJS) offering strength of up to 400 MPa [12]. Austempered ductile iron (ADI) is a material having twice the tensile and yield strength of standard ductile irons (GJS), and 50 percent higher fatigue strength than these alloys [13, 14].

High strength castings

ADI is a cast iron material in which carbon is present as graphite nodules and the matrix containing the nodules is ausferrite, a fine-grained mixture of ferrite and stabilized austenite that provides the high strength and ductility of ADI by a mechanism similar to the TRIP (transformation induced plasticity) effect in steel. ADI is produced by a heat-treating cycle (**Figure 11**) applied to cast ductile iron to which nickel, molybdenum or copper have been added in the ranges shown in **Table 6**. Cooling from the austenitizing temperature to the austempering temperature must be rapid enough to avoid pearlite formation [13], which reduces strength, elongation and toughness. The addition of Mo, Ni and Cu shifts the pearlite nose towards longer times and promotes hardenability. In general, section sizes greater than 19 mm require alloying. Alloying with Mn is not recommended because it segregates to the regions between graphite nodules. It delays the austempering reaction there, and can result in martensite formation and reduced toughness. Copper additions in excess of 0.80% can create diffusion barriers around the graphite nodules that inhibit carbon diffusion during austenitizing. Ni additions of up to 2% are technically and economically viable. Molybdenum is very powerful in delaying both pearlite and bainite formation, hence promoting the formation of metastable carbon-enriched austenite. However, it strongly segregates to intercellular/interdendritic locations between the graphite nodules where it can form hard Mo carbides [14]. These carbides are undesirable, especially if a component is to be machined after heat treatment. The Mo alloy content is usually limited to 0.3% because of this effect.

Table 6. Ranges of main alloying elements for austempered ductile iron.

Alloy content (mass %, min./max.)				
C	Si	Cu	Ni	Mo
3.5/3.7	1.9/2.3	0.6/1.0	0.6/2.5	0.15/0.3

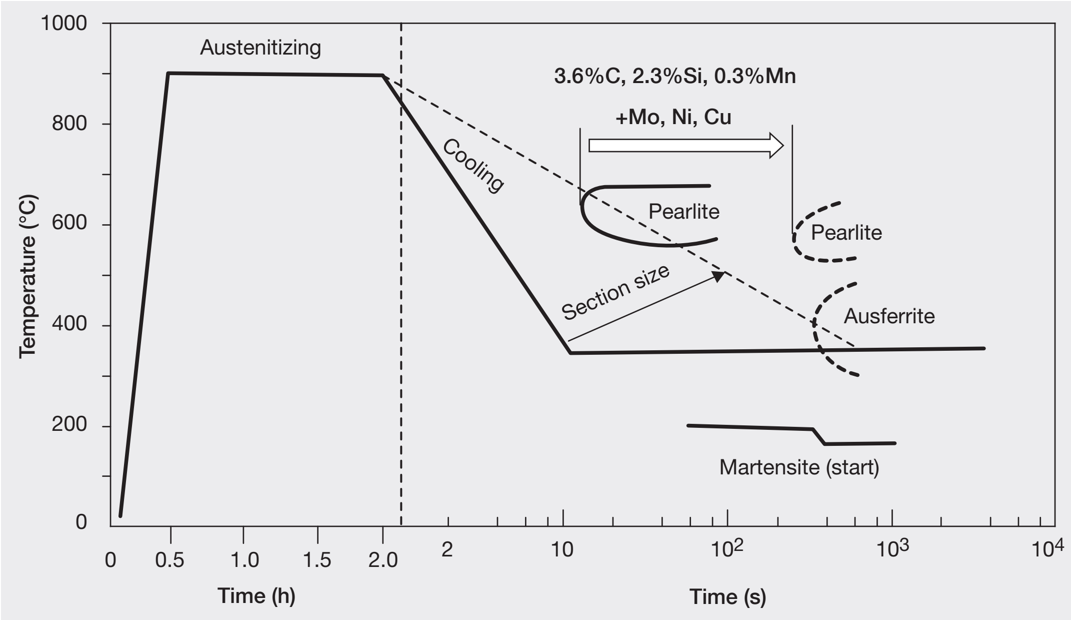

Figure 11. Schematic heat treatment cycle and CCT transformation diagram for the production of austempered ductile iron (ADI).

High-performance gear steels

Higher-power wind turbines usually have a gearbox that converts the low-speed rotor shaft rotation into the high speeds required by the generator. The gears in wind turbines are sometimes exposed to extremely high loads at the flanks and toes of the gear teeth, for example during sudden changes of wind speed or hard stops. Most failures and breakdowns of wind turbines occur, therefore, in the gearbox, leading to significant outages and replacement costs. A hard case and a tough core are needed for a more wear-resistant gear, capable of handling high impact loads [15]. Gearboxes for wind turbines have also been specifically developed for quiet operation with reduced mechanical noise. Gear noise increases during the turbine's lifetime due to abrasion of the gear tooth surface. Consequently, increasing the surface hardness and abrasion resistance of gears can also reduce noise. Typical low-alloy case-hardening steels such as 16MnCr5, 20MnCr5 or 27MnCr5 cannot be used for wind turbine gear applications, which require long fatigue life and high toughness. High-performance NiCrMo carburizing steels as specified in **Table 7** provide deep hardening ability and have strong resistance to fatigue. Currently, the grade 18CrNiMo7-6 is the standard gear steel for windmill gearboxes.

The following strategies can further improve carburizing steels for large and heavily loaded gears:

- Increase the core tensile strength and toughness
- Increase the fatigue strength in both core and case
- Improve the hardenability
- Reduce the quench distortion, with resulting improvement of reproducibility
- Improve microstructural stability to withstand elevated temperatures during service.

Additionally, a typical near-surface defect in a carburized layer, the intergranular oxidation layer, has to be avoided because it can initiate fatigue fracture and reduces the fatigue strength of the tooth. The

Table 7. Range of main alloying elements for high-performance carburizing steel used in large transmissions.

Steel grade	Material number	Alloy content (mass%, min./max.)					
		C	Si	Mn	Cr	Mo	Ni
17NiCrMo6-5	1.6566	0.14/0.20	≤0.40	0.60/0.90	0.80/1.10	0.15/0.25	1.20/1.50
20NiCrMoS6-4	1.6571	0.16/0.23	≤0.40	0.50/0.90	0.60/0.90	0.25/0.35	1.40/1.70
18CrNiMo7-6	1.6587	0.15/0.21	≤0.40	0.50/0.90	1.50/1.80	0.25/0.35	1.40/1.70
14NiCrMo13-4	1.6657	0.11/0.17	≤0.40	0.30/0.60	0.80/1.10	0.10/0.25	3.00/3.50

soft zone caused by intergranular oxidation results in surface softening in the carburized layer [16]. Eliminating surface structure anomalies is thus an important subject in the development of high-fatigue-strength gears. The toughness can be improved effectively by raising the tempering temperature. However, this requires improving the tempering resistance in order not to lose strength. A fundamental way to deal with these issues is to adjust the chemical composition of the carburizing steel. Accordingly, the chemical composition of carburizing steels can be further developed to achieve the above goals using the following guidelines:

- Prevent intergranular oxidation → reduce Si, Mn, and Cr.
- Improve hardenability → increase Mo.
- Improve toughness → increase Ni and Mo.
- Refine and homogenize grain size → balance Nb, Ti, Al and N microalloying addition.
- Strengthen grain boundaries → reduce P and S.

Figure 12 illustrates the results of such an alloy optimization, starting from a standard 18NiCrMo7-6, by showing Jominy curves of non-carburized base material [15]. Steel with 0.18% C can achieve a maximum martensite hardness of 49 HRC. The standard material nearly reaches this value at the surface. In a modified concept, where the Ni content is further increased and Mo is reduced, the hardness towards the core increases due to enhanced bainite formation. However at the surface, where the highest hardness is needed, the material softens due to an increased formation of residual austenite. In contrast, the modified concept with increased Mo content shifts the entire Jominy curve up towards higher hardness [15, 17]. Thus, the surface becomes harder and the core is strengthened as well. The hardness can even exceed the maximum martensite hardness due to the formation and dispersion of ultra-hard Mo or Nb carbides. This higher- hardness core of a carburized gear offers better mechanical support to the carburized case or a potential hard surface coating. Simply raising the bulk carbon content would, of course, also raise the hardenability of the steel, but the equally important toughness would drop too much.

After quenching, the carburized component is tempered to improve its toughness. The tempering temperature has to be optimized so that the toughness of the steel improves without giving up too much of its strength. In case-hardening steels like 17NiCr6-6, 15NiCr13 or 14NiCrMo13-4, the mechanical properties of the case decrease rapidly for tempering temperatures higher than 180°C. Because of that, critical applications are restricted to a maximum operating temperature of 120/160°C, making gearbox cooling an important issue. The tempering resistance of a steel can be strongly improved by significantly increasing its Mo content and optionally adding Nb. **Figure 13** demonstrates that the addition of 2% Mo instead of the standard 0.25% provides a hardness greater than 700 HV (60 HRC) even after tempering at 300°C [18].

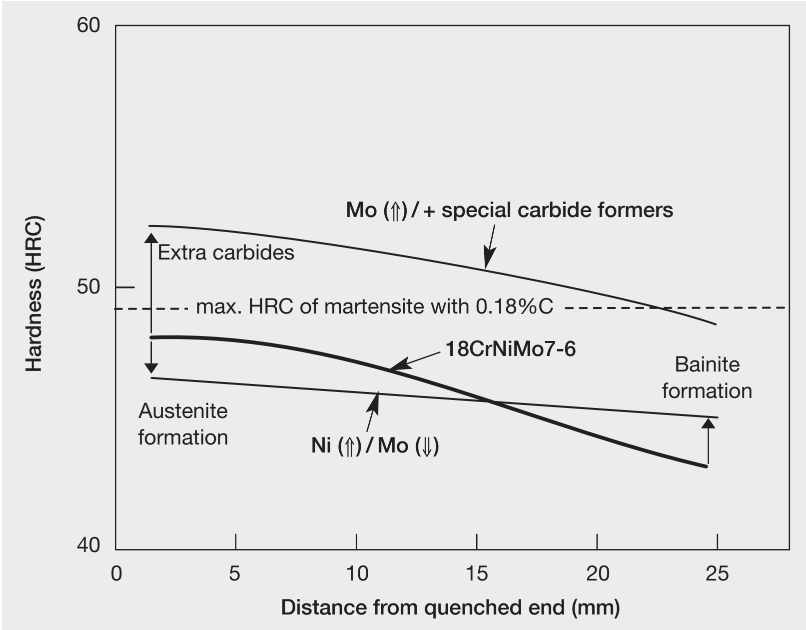

Figure 12. Alloying concepts for the modification of 18CrNiMo7-6 to obtain improved performance of windmill gearboxes.

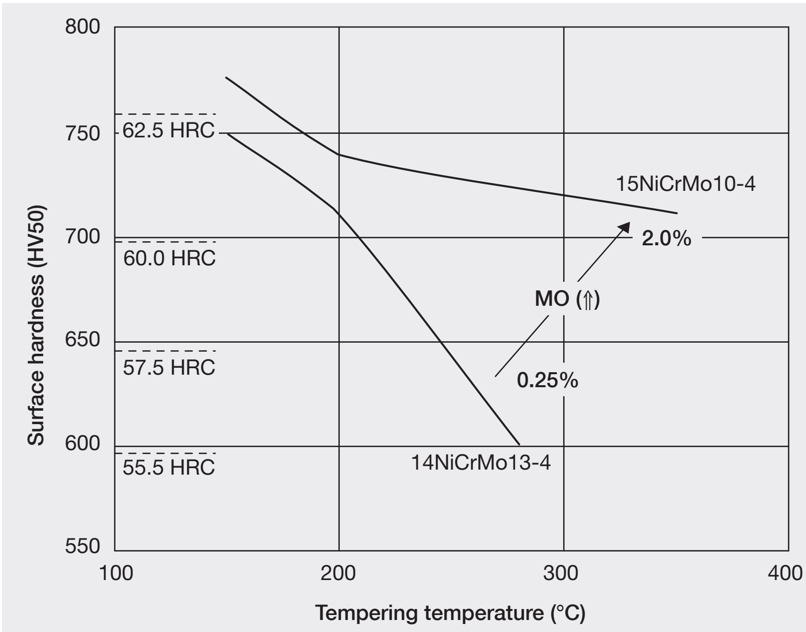

Figure 13. Hardness of the carburized case on quenched & tempered substrates demonstrating the effect of Mo on the tempering resistance.

Raising the carburizing temperature is an opportunity to reduce cost substantially. Since carbon diffuses more quickly into the surface layer at higher temperatures, the treatment time required to achieve a specified case depth is reduced significantly. At the standard carburizing temperature of 950°C, a carburization depth of 1.0 mm is achieved after about five hours. However, at 1050°C the same carburization depth is reached in only two hours, representing a time saving of 60 percent [19]. There is one obstacle to applying this increase in carburizing temperature to standard carburizing grades: excessive grain growth. Performance requirements for wind power generators require an austenitic grain size smaller than ASTM 5 after carburization, with no more than 10 percent of individual grains having size ASTM 3 and 4. Recent research shows that a balanced addition of Nb, Ti, Al and N leads to precipitates that impede grain growth even after long times at 1050°C. **Figure 14** compares the grain size distribution of standard and Nb-Ti modified 18CrNiMo7-6, treated at 1030°C for 25 hours. The modified grade fulfills the minimum grain size demands, and has a narrower grain size distribution. The smaller grain size is beneficial for the fatigue properties and a narrow size distribution avoids geometrical distortions after the heat treatment, reducing costly finish machining of the hard material.

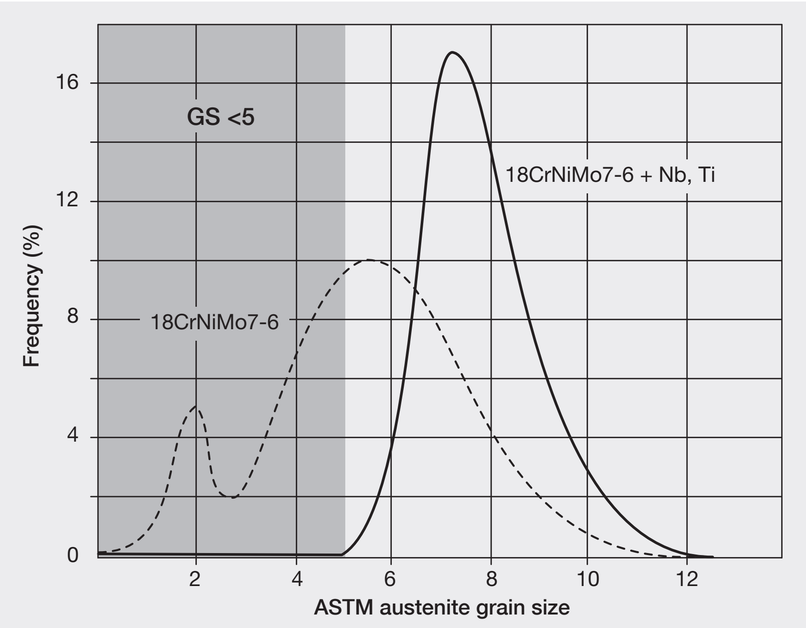

Figure 14. Effect of microalloying in modified 18CrNiMo7-6 steel on the austenite grain size distribution after high temperature carburizing at 1030°C for 25 h; a grain size below ASTM 5 is typically not accepted for demanding applications.

These examples show that there is much room for materials advances to improve the cost and efficiency of wind power generation equipment. As the industry is moving towards larger turbines and harsher operating conditions (e.g. offshore), weight reduction, especially of the nacelle, as well as higher reliability will be necessary. Molybdenum alloying can help accomplish this reduction by increasing the strength of the involved materials and improving their resistance against premature failure caused by wear or fatigue in key components of the windmill.

Economic and Ecological Aspects of Alloy Upgrading

These examples clearly show that upgraded iron and steel alloys offer opportunities for equipment weight savings and improved reliability of key components in clean and green energy generation facilities.

Naturally, higher alloy contents make these materials more expensive, and this additional cost must provide benefits. In all the case studies outlined here, this cost-benefit analysis reveals an unequivocally positive result. In the case of upgrading the steel of a wind tower structure from S355 to S500 or a penstock from S500 to S890, respectively, a weight saving of 30% can be achieved under constant load conditions, if the design is governed by tensile stress. The purchase cost increase for the upgraded steel grades is in the range of 20 to 25% per ton. Thus, the balance at that stage is already positive since 30% less material needs to be purchased. Further savings result from lower transport and erection costs, i.e., welding and hoisting efforts. Finally, by producing a smaller amount of stronger steel, less CO_2 is generated, further improving the total CO_2 life-cycle balance of these clean and green power generation methods.

Upgrading a 18CrNiMo7-6 gear steel in the proposed manner would increase the Mo content from around 0.3% in the standard alloy to 0.5% in the modified alloy. The additional alloying cost for the extra amount of molybdenum is, however, only a fraction of what a one-day downtime of the windmill causes in loss of income should the gearbox fail. Microalloying this steel grade with Nb and Ti reduces the carburizing time by up to 60%, leading to major processing cost savings and to significant reduction of the component's CO_2 footprint.

References

1 International Energy Agency, IEA Energy Statistics, www.iea.org.

2 T. Kamo, H. Sakaibori, K. Onishi, T. Kawabata and S. Okaguchi, *Metallurgical Basis of 950MPa Class High Tensile Strength Steel (HT950) Plates for Penstock*, International Steel Technology Symposium, Kaohsiung (Taiwan), 2008.

3 ThyssenKrupp Steel Europe, *N-A-XTRA® and XABO® high-strength steels – Processing recommendations*, www.thyssenkrupp-steel.com.

4 F. Hanus, F. Schröter and W. Schütz, *State of art in the production and use of high-strength heavy plates for hydropower applications*, Conference on High Strength Steel for Hydropower Plants, Graz (Austria), 2005.

5 K. Hayashi, A. Nagao and Y. Matsuda, JFE TECHNICAL REPORT, No. 11 (June 2008), p. 19.

6 N. Enzinger, H. Cerjak, Th. Böllinghaus, Th. Dorsch, K. Saarinen and E. Roos, *Properties of High Strength Steel S890 in Dry and Aqueous Environments*, 1st International Conference on Super-High Strength Steels, Rome (Italy), 2005.

7 Ming Li and Wenlin Jiang, *The Application and the Problems of High Strength Steel on Penstock in Chinese Hydroelectric Stations*, ISIJ International, Vol. 42 , No. 12 (2002), p. 1419.

8 K. Nishimura, K. Matsui and N. Tsumura, JFE TECHNICAL REPORT, No. 5 (Mar. 2005), p. 30.

9 International Energy Agency, *Technology Roadmap Wind Energy*, www.iea.org.

10 NN., Supply Chain: *The race to meet demand*, Wind Directions – January/ February 2007, p. 27.

11 J. Goesswein, *Operational Results of World's Largest Wind Energy Converter REpower 5M and Project Status of the First Offshore Wind Farm using 5 MW Turbines*, 5th Symposium on Offshore Wind and Other Marine Renewable Energies in Mediterranean and European Seas, Civitavecchia (Italy), 2006.

12 H. Roedter and M. Gagné, *Ductile Iron for Heavy Section Wind Mill Castings*, Keith Millis Symposium on Ductile Cast Iron, Hilton Head Island (USA), 2003.

13 R.B. Gundlach, J.F. Janowak, S. Bechet and K. Röhrig, *Transformation Behaviour in Austempering Nodular Iron*, The Physical Metallurgy of Cast Iron, MRS Vol. 34 (1985), p. 399.

14 K. Hayrynen, *The Production of Austempered Ductile Iron*, 2002 World Conference on ADI, Louisville (USA).

15 F. Hippenstiel, K.-P. Johann and R. Caspari, *Tailor Made Carburizing Steels for Use in Power Generation Plants*, European Conference on Heat Treatment 2009, Strasbourg (France).

16 M. Uno, M. Hirai and F. Nakasato, *Effect of Alloying Elements on the Properties of Cr-free Carburizing Steels*, The Sumitomo Search No. 39, September 1989, p. 33.

17 L. Flacelière, Th. Sourmail, E. d'Eramo, P. Daguier, H. Dabas and J. Marchand, *Steel solutions designed for wind mills*, European Conference on Heat Treatment 2009, Strasbourg (France).

18 G. Gay, *Special Steels for New Energy Sources*, European Conference on Heat Treatment 2009, Strasbourg (France).

19 F. Hippenstiel, *Tailored Solutions in Microalloyed Engineering Steels for the Power Transmission Industry*, Materials Science Forum Vols. 539-543 (2007), p. 4131.

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