Steels for modern steel construction and offshore applications

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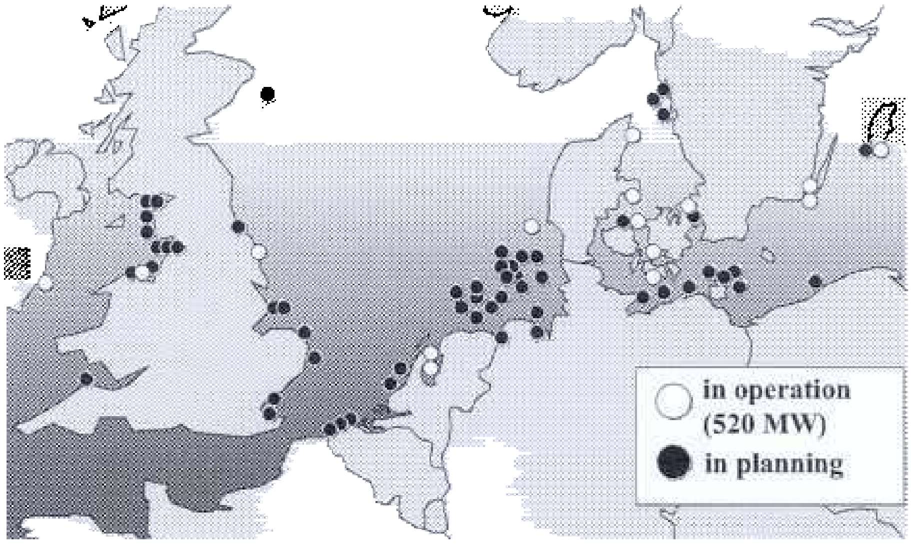
Abstract

Wind energy is going offshore !
It is understood, that these new constructions set new requirements on the quality of steel products used. Fortunately, plenty of experiences exist in the production and fabrication of steel products for the construction of offshore oil and gas drilling platforms. From these also offshore windmill construction will strongly benefit.
The material developments done in the offshore sector are strongly link to the thermomechanical rolling process for steel plates. The possibilities of this process and the resulting material properties will be presented in detail. However, even more conventional steel structure such as steel bridges are supposed to benefit form these developments.

1. Introduction

In most European countries there is a strong tendency to increase the share of renewable energy on the total energy consumption. This process is also forced by political circumstances such as the Kyoto-protocol. Wind energy is understood to be such a proper energy and is - therefore - promoted by some countries which created also ways in order to financially support this form of energy. Thus, by the end of the year 2003 more than 28.000 MW have been installed in conventional onshore windmills in EU 15. However, due to the starting lack of wind-efficient sites and the resistance of neighbourhood because of noise induction from the engines and the tourism damaging view envious plans have been developed to "put" windmills offshore. In particular countries such as Germany, Great Britain and the Netherlands are supporting this technology (Figure 1).



Source: fascination offshore - report 2003

Figure 1: Existing and planned offshore wind parks in Europe

Of course, by steadily blowing strong wind on the sea the efficiency of these engines can strongly be increased. However, the loading conditions characterised by the superposition of waves and wind are much more severe. Furthermore, offshore windmills tend to be of bigger size than onshore windmills in order to minimise the infrastructure costs for grid connection and foundations. This leads to more pretentious steel structures not only in the tower being of bigger size. Furthermore, water depths up to 30 m result in foundations consuming even more steel than the engine-carrying tower. Figure 2 describes types of foundations used for offshore windmills.

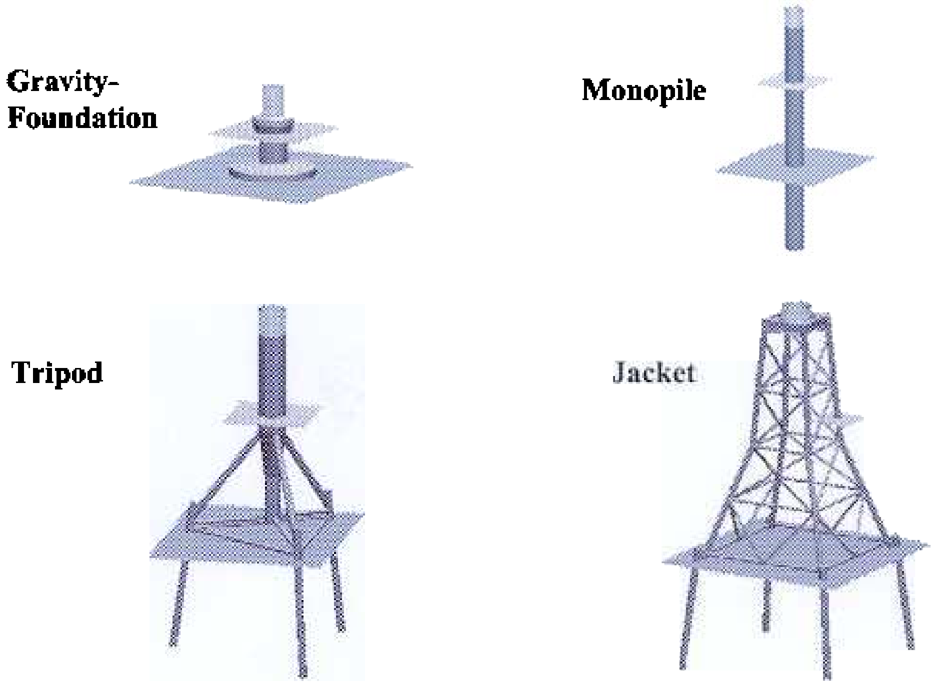


Figure 2: Types of foundation in offshore windmills

However, wind energy is only following a way defined by fossil energies oil and gas some 60 years ago. After initial scepticism and a long learning period offshore oil and gas drilling is today a blossoming branch which is also able to construct platforms up to a sea depth of 3000 m and a design temperature down to -40°C. For this branch steel industry has developed new kinds of steel with excellent mechanical as well as fabrication properties. Today offshore wind energy can profit from this knowledge.

2. Requirements on modern steel for offshore construction

In general most steel constructions in offshore engineering are designed to perform an optimum between the two poles safety and reliability on the one hand and economical efficiency on the other hand. Maybe that this balance is a little bit different for offshore windmills in comparison to drilling platforms as failure of a windmill must not have an impact on life and health of human beings. Nevertheless it can be stated that there is a strong link between efficiency and safety, what will be highlighted on some examples.

For instance, it is understood that the weld is normally the weakest part of a structure in which cracks arise and grow. Therefore, avoiding of not necessary welds not only increases efficiency but also the safety of the construction. This can be achieved by employing the entire production range steel plants offer today, that means plate widths up to 5200 mm, lengths up to 28 m and plate unit weights up to 36 t.

Furthermore, offshore construction normally applies for steel grades whose toughness values are by far higher than those of conventional structural steel. Excellent toughness values are directly linked to good fabrication properties in particular weldability. Thus, an easy fabrication (for instance the use of highly efficient welding processes) and also for a safe erection in the hostile sea conditions are enabled by guaranteeing good toughness values also in the heat affected zone (HAZ) after welding.

In order to have a sure knowledge how the steel behaves after welding, offshore steel grades are normally approved by special fracture mechanical testing. Here, in particular the CTOD-test (crack tip opening displacement) has gained importance and is applied for the HAZ of the steel. By this tool it can be investigated how a crack forms and grows in this - as mentioned above - most sensitive part of the structure - and good predictions of the service life can be given. Thus, Figure 3 shows an micrography of the CTOD-test in the HAZ, where the crack is initiated in the most sensitive zone, the coarse-grain zone.

The positive effect of CTOD-testing is confirmed by some construction and fabrication codes allowing neglecting of expensive stress relieving procedures if steel with CTOD is applied.

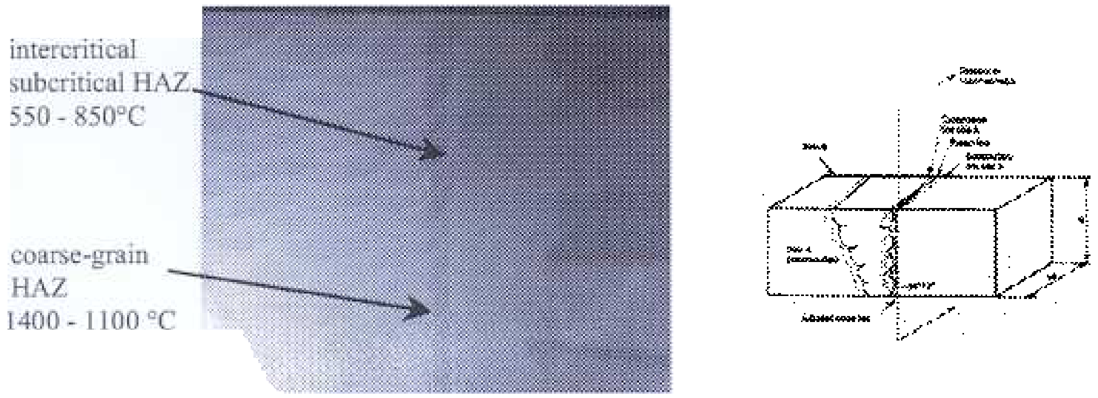


Figure 3: CTOD in the HAZ of a steel

3. Production of modern steel

The demand for high yield and other strengths in large diameter linepipes combined with high toughness' at low temperatures and excellent weldability have resulted in the development of "Thermo-Mechanical rolling", the extremely diverse forms of which can nowadays be grouped together under the umbrella term "TM" (or TMCP = Thermo-Mechanical Control Process).

Figures 4 compares the various types of TM-processes with the more classical production routes used in a rolling mill which provide a more separate rolling and heat treatment.

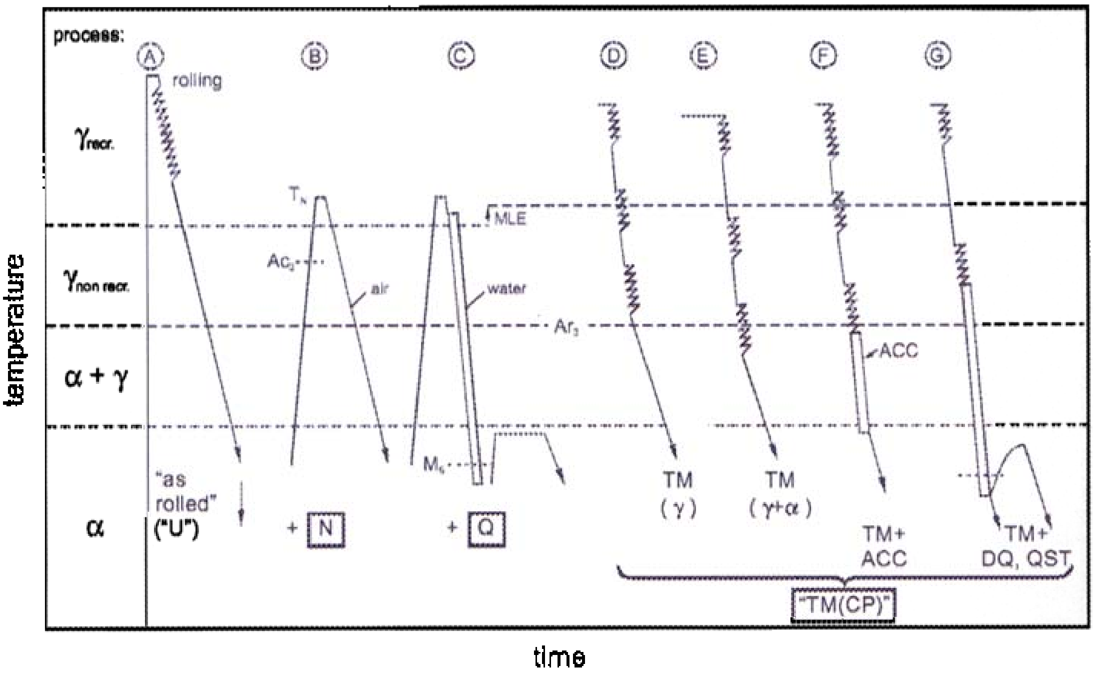


Figure 4: Time-temperature scheme for various processes

A: The steel plate is delivered in state "U" (non-heat-treated, or "as rolled"), without any further modification of the structure by means of heat-treating.

A structure with a typical combination of properties can be achieved by means of following heat treatment, as

B: Normal rolling + heat treatment "Austenitization (>Ac_3, approx. 900° C) + cooling in air"
= Normalising (N)
The result is a structure consisting predominantly of polygonal ferrite and pearlite. The delivery state is abbreviated to "N". Higher yield and tensile strengths can essentially be achieved for normalised steels only by means of higher alloying element contents; there are therefore limits on the possible property combinations achievable in the heavy plate using this process. An equivalent state can be achieved by means of normalising rolling, i.e., rolling with final deformation in the N-temperature range, which is therefore also designated as "N".

C: Normal rolling + heat treatment "Austenitization (>Ac_3) + water quenching"
= Quenching (or hardening).
Due to the extremely high rate of plate cooling, the result is a hard structure consisting predominantly of martensite and bainite. The delivery state is abbreviated by "Q".
The toughness of the structure is increased by modifying the originally hard and brittle martensite zones by means of subsequent tempering (in a further roller hearth furnace, for example, at temperatures of around Ac_1 –100° C, i.e., approx. 600° C). A heat-treated structure with a combination of a still relatively high hardness or yield and tensile strength with systematically adjusted toughness results. Quenched and tempered steels are used in particular where requirements for strength or/and resistance to wear are especially high.

In comparison to these production routes TM-rolling is used not only as a shaping process but also systematically for the achievement of the specific combination of properties required. TM-rolling can therefore be defined as a process which aims at achieving a structure with a fine effective grain size, permits a favourable combination of service properties, is tailored to the steel composition, and is composed of a sequence of the following steps controlled in terms of time and temperature:

- Exact definition of the chemical composition, often with microalloying
- Slab reheating: with a defined drop out temperature
- Rolling: on the basis of a specified pass sequence with finish rolling in the non-recrystallizing austenite or (α+γ) two phase zone;

  Cooling: either in air or in the stack, or in accelerated form in the cooling line, down to a defined final cooling temperature;

  Possibly, additional heat treatment (tempering).

Figure 5 illustrates the installation necessary for this process in a rolling mill.

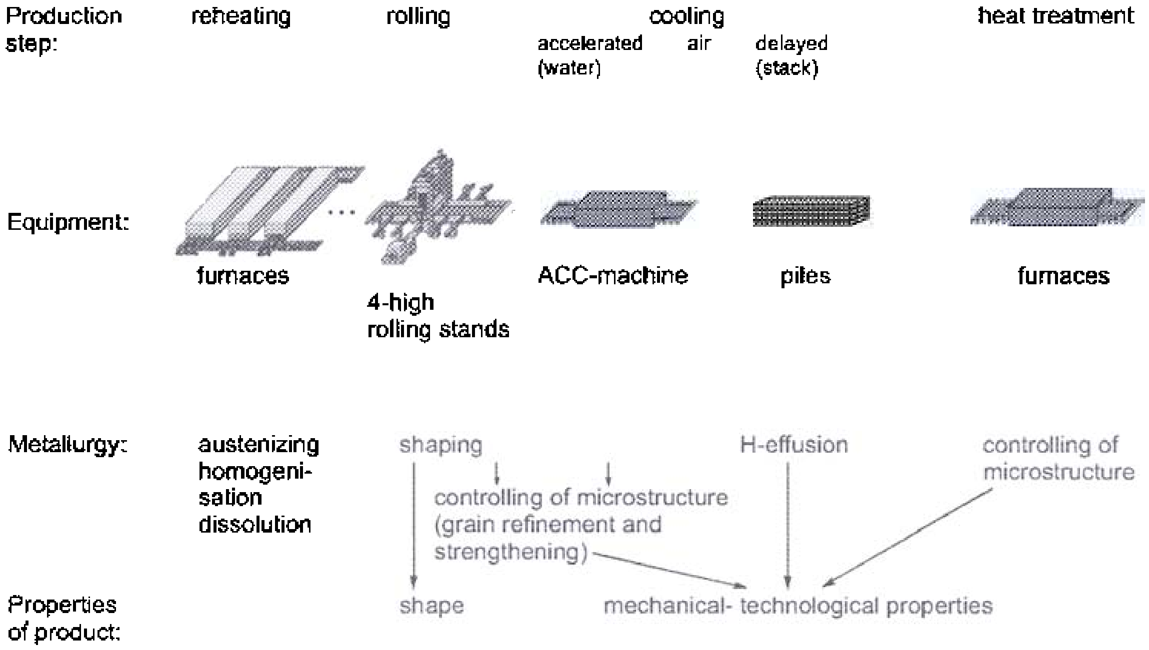


Figure 5: Process steps in the plate mill and their metallurgical objective

4. Properties of modern TM-steel

By the application of the thermomecanically rolling process, a very fine grain structure of the steel can be achieved. According to the Hall-Petch-relation the yield stress increases with decreasing average grain size. Therefore, the production of higher strength steel grades is enabled without extensive alloying as it is normally done by normalised steel grades. This has also a positive impact on ductility as alloying with common alloying elements used to increase the strength (carbon, manganese) may worsen the toughness of the steel. Thus, Figure 6 illustrates the achievable yield stress as a function of the alloying content expressed by the carbon equivalent CE (IIW) for TM-steel and conventional normalised steel.

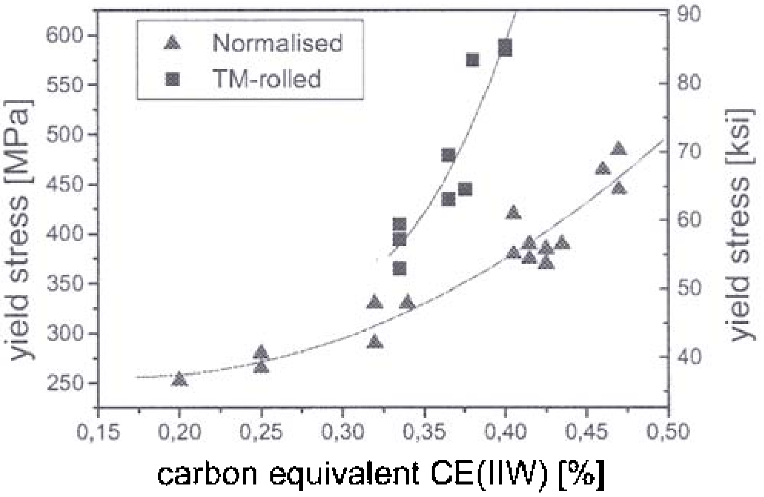


Figure 6: Dependence of achievable strength on carbon equivalent and rolling process

Thus, EN 10 113-3 defines TM-steel for use in constructional steelwork in yield stress grades up to 460 MPa. These grades are given in Table 1. For more information about this kind of steel reference is made to [1-3]

	Tensile strength R_m [MPa]	Yield strength R_{eH} [MPa]			Elongation A_5 [%]	Charpy - V Impact test	
		≤ 16 mm	> 16 mm ≤ 40 mm	> 40 mm ≤ 150* mm		Temperature [°C]	Energy [J]
S355M	450- 610	355	345	335	22	-20	40
S355ML						-50	27
S420M	500 - 660	420	400	390	19	-20	40
S420ML						-50	27
S460M	530 - 720	460	440	430	17	-20	40
S460ML						-50	27

Table 1: Mechanical properties of TM-steel for constructional steelwork acc. EN 10 113-3 (*: flat products today only defined up to 63 mm thickness though feasible up to 120 mm)

As discussed in section 2, additional requirements may be set on steel products used in offshore construction. Usually for offshore construction steel according to the standards API 2H, 2W or 2Y (in yield grades of 50 and 60 ksi), EN 10 225, BS 7191 (EM(Z)350 - EM(Z)450) or the Norsok-description are used. Here, the Norsok-standard also defines TM-rolled steel up to a yield stress of 500 MPa, which has already been used in the first drilling platforms. Table 2 gives a detailed description of the mechanical properties of some higher strength grades in the Norsok standard and also a typical chemical composition, by which these steel grades can be realised. It can be clearly seen, that also an S500M3Z-grade shows very low carbon equivalents in spite of the higher yield stress. Here, usually the P_{cm} equivalent,

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + \frac{Ni}{60} + 5B,$$

by which the tendency of cold-cracking in the heat affected zone is judged, is of special importance.

Steel name	Tensile test, trans			Charpy-V impact test, trans	Through-thickness test	
	R_{eh} [MPa]	R_m [MPa]	A_5 [%]	CVN [J] at -40°C	Z [%]	R_m [MPa]
S420M3Z	500-660	≥ 420	≥ 19	surface + mi-thickness: ≥ 60 (42)	35 (25)	≥ 400
S500M3Z	600-750	≥ 500	≥ 17	surface + mi-thickness: ≥ 60 (42)	35 (25)	≥ 480

	C	Mn	Ni	Cu	Mo	Nb+V+Ti	P_{cm}
S420M3Z	0.09	1.44	0.22	0.15	0.05	0.02	0.19
S500M3Z	0.06	1.58	0.54	0.28	0.15	0.02	0.18

Table 2: High-strength steel for offshore application acc. to Norsok; mechanical properties and typical chemical composition (50 mm thickness)

As described in the section above, the properties of TM-steel are not only influenced by the chemical composition but also by the rolling technique and also the finishing cooling conditions [4]. Thus, the mechanical properties of the steel can also be varied by a change in the cooling conditions. Figure 7 shows for instance, how the yield and tensile strength can be raised by maintaining the chemical composition of the steel. A transfer from a normal cooling process (ACC) to the heavy accelerated cooling (HACC) characterised by much higher cooling rates in the beginning of the cooling process results in an increase of the yield strength of almost 60 MPa.

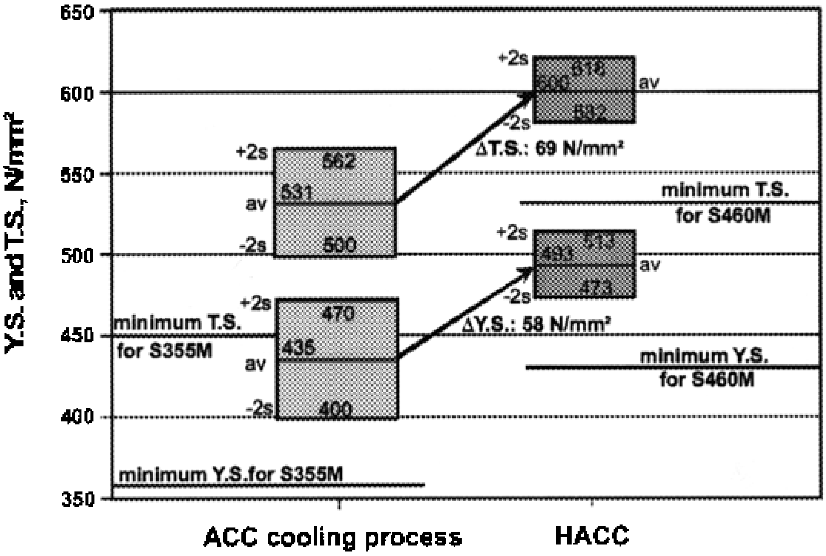


Figure 7: Increase of yield and tensile strength by heavy accelerated cooling

The explanations above have already indicated that the production of higher-strength yield grades is not the only advantage of TM-steel. Due to relatively low alloying contents and the good ductility not only the welding process is facilitated by reducing or even completely omitting preheating and being able to choose higher heat inputs necessary for highly productive automatic welding (for instance: longitudinal and circumferential welds of monopile and tripod tubes). Furthermore, best toughness values can be provided in the heat affected zone after welding.

For instance, Figure 8 illustrates the Charpy-V-transition curve measured in the heat affected zone (HAZ) of a butt weld performed by the SAW process at an line energy of 3.0 KJ/mm for an S355ML-steel. In can be seen, that even at this very high heat input excellent toughness values can be obtained in the HAZ ensuring a high safety and reliability against brittle fracture of the weld.

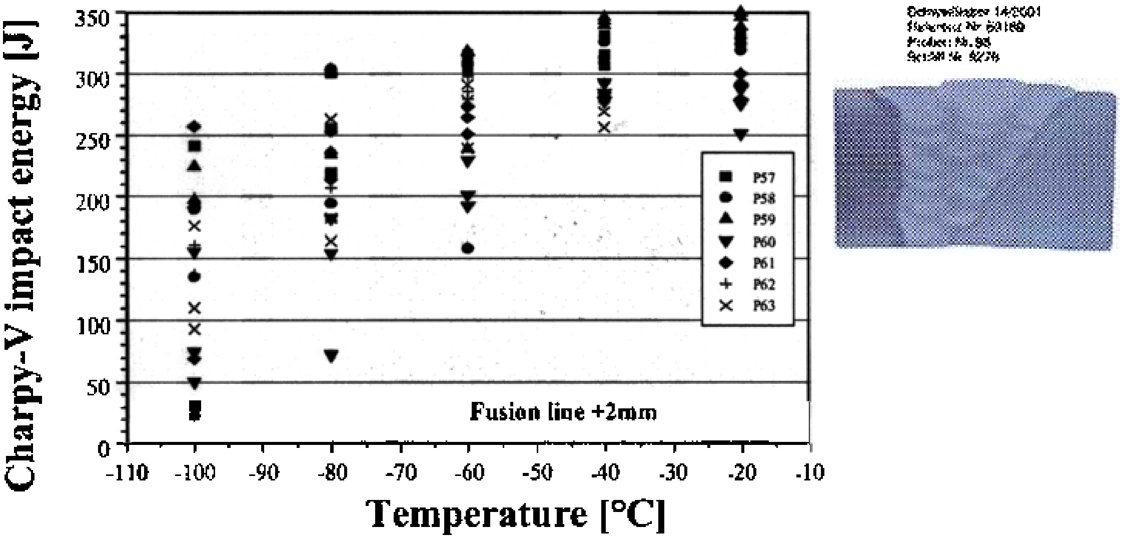


Figure 8: Charpy-V-Temperature-curve in the HAZ for a butt weld of S355ML (50 mm) with SAW-process (E = 3.0 KJ/mm)

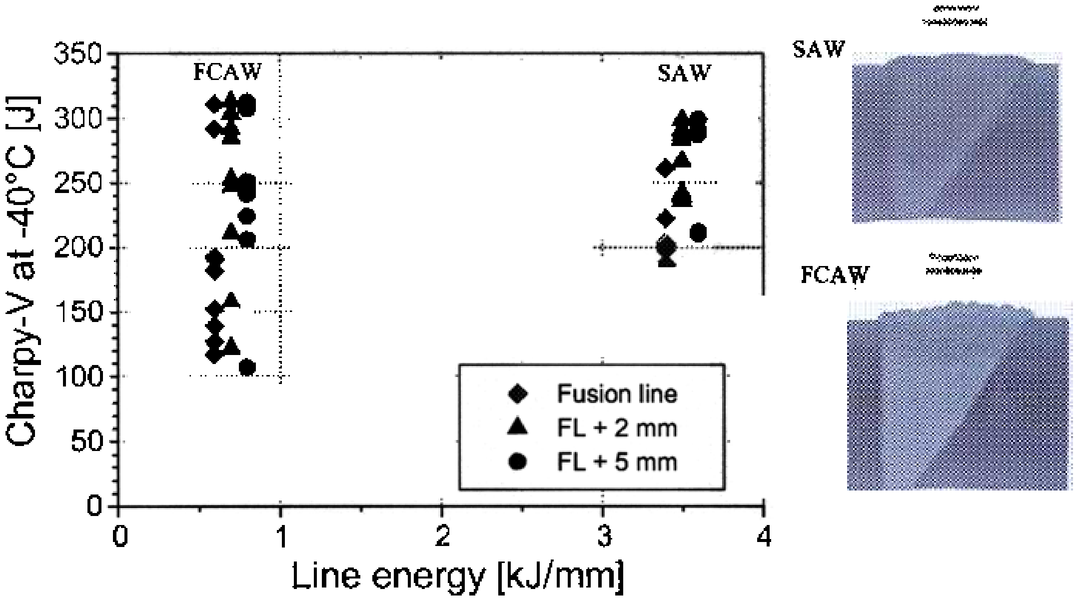


Figure 9: Charpy-V-toughness values in the HAZ for a butt weld of S500M (70 mm) for different welding processes SAW (Submerged arc welding) and FCAW (flux cored arc welding)

This excellent toughness values in the HAZ are also confirmed by Figure 9 comparing different welding processes with different heat input and also various positions in the HAZ even for higher strength grades.

In particular for lower heat inputs used by manual welding techniques the hardenability of the steel in the HAZ is an important criterion for judging weldability. For small cooling rates, normally expressed by the cooling time between 800°C and 500°C $t_{8/5}$, highly alloyed steels result in high hardness values in the HAZ with the risk of cold cracking. Due to the low alloying content of TM-steel also steel grades with a yield strength of 500 MPa show very low hardness values in the HAZ as shown in Figure 10. Therefore, the risk of cold cracking for such grades can be assumed to be very small.

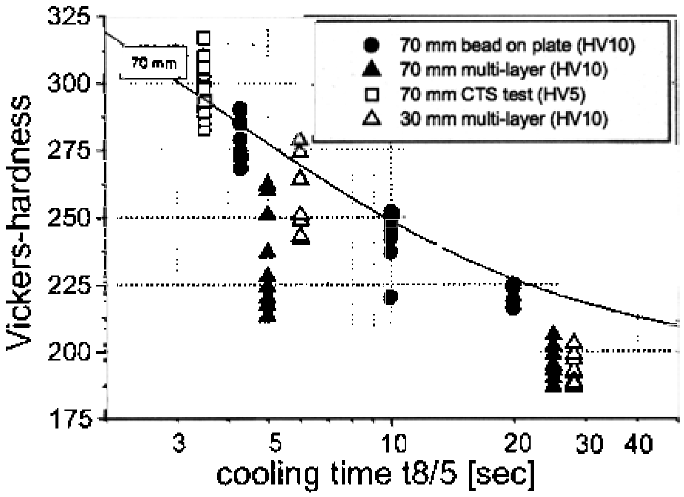


Figure 10: Hardenability of an S500M during welding

5. Examples from various branches

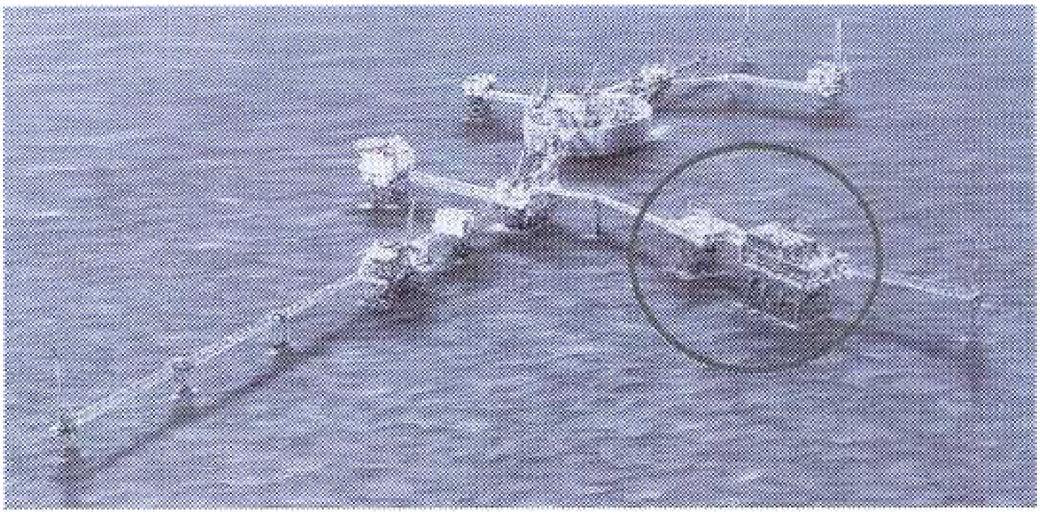


Figure 11: Ekofisk II-platforms

Since years TM-rolled higher-strength steel grades are successfully applied in oil-and gas drilling applications such as the extension of the Ekofisk-project next to the Norwegian coast shown in Figure 11. About 45.000 t of plates predominately of the steel grade S420M-Offshore were used for these two platforms. The six-legged platform 2/4X weighs 7900 t, the jacket alone already 5800 t (not including the ram piles for the foundation into the sea bottom). The new central platform 2/4J consists of a 11400 t jacket tied to sea bottom by 16 ram piles of a total weight of 5500 t and carries the deck with a weight of 23000 t. The two platforms stand about 90 m above sea level and are connected to each other and the total complex by several bridges.

The TM-steel grades won also recognition in the onshore construction, for instance in bridgebuilding such as the new Rhine-bridge in the north of Düsseldorf (Germany), which was opened for traffic middle of 2002 [5]. For this cable-stayed bridge with a central span length of 275 m the pylons had to be restricted to a height of 34 m due to their situation in the landing zone of the near airport. Therefore, the high forces arising in the pylon heads could only be solved by selecting the high-strength steel S460ML for these structure elements. Even plate thickness' up to 100 mm have been used for the central parts of the pylon heads. The Prince Claus bridge in Utrecht (The Netherlands) represents another recent example for the application of S460M in the pylon of cable bridges. For this project more than 1,300 t of S460M/ML have been used. Figure 12 illustrates the pylons of the two bridges.

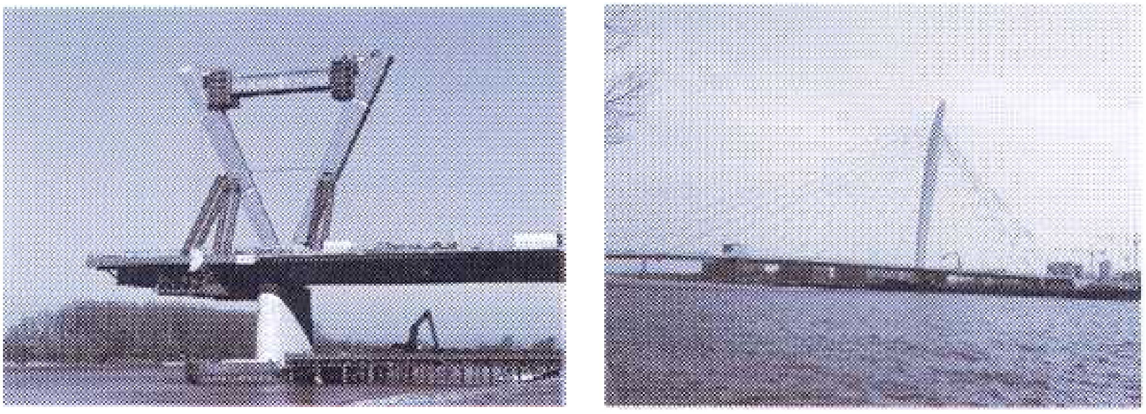


Figure 12: Cable stayed bridges Düsseldorf-North (left) and Prince Claus (right)

However, higher strength steel grades are not only used in highly stressed structural elements such as pylons. Even in more common structural parts such as girders or deck elements the application of higher strength grades can result in minimised structural cross section allowing economies in fabrication and erection too. One prestigious example is given in Figure 13: The Millau-Viaduct will be opened for traffic beginning of 2005 and will have the reputation of the highest bridge in the world (343 from the valley ground to the top of the pylons) as well as the longest cable-stayed bridge in the world (2460 m). For the pylon heads as well as the construction of the box girder more than 21,000 t of S460 have been used - with a total quantity of heavy plates of 43,000 t.

Figure 13: Millau-Viaduct - Future 2005 and current state November 2003

Shipbuilding industry has been among the first users of TM-plates. Here these plates in thickness' up to 80 mm can be efficiently applied for instance in the upper girder of boxships due to the improved weldability in comparison to conventional steel in the same thickness. Another example is described by Figure 14. The Mayflower TIV, a special-purpose ship for quick erection of offshore windmills even at most severe environmental conditions, has been built by a Chinese shipyard with more 5.300 t of NV-E/F36 and NV-A/D/E/F500, shipbuilding grades with a yield stress up to 500 MPa and Charpy-impact values tested up to -60°C. Thickness' up to 75 mm have been produced by the TM-process, whereas for thicker plates the quenching and tempering process has been required.

Figure 14: Mayflower TIV - Offshore windmill erection

6. Summary

Offshore windmills planned today in many European countries set much higher requirements on the steel quality than usual onshore installation. Not only the dimensions of steel products applied, especially the thickness, will increase. Higher ductility requirements may demand the utilisation of modern steel grades such as thermomecanically rolled steel presented in this paper. This kind of steel not only offers best safety and reliability. Furthermore, they are the basis for an excellent fabrication efficiency due to their good weldability and formability. Thus, these steels can also be employed for highly efficient welding procedures necessary for the serious production of windmills as shown in Figure 15.

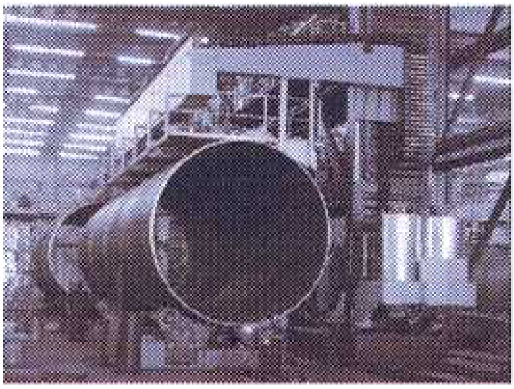


Figure 15: Circumferential welding of monopiles (SAW, 3-wire; foot: SIF group)

7. References

[1] Hubo R.; Hanus F. E.; Streißelberger A.: *Manufacturing and fabrication of thermomecanically rolled heavy plates*, Steel Research, Vol. 64, No 8/9 (1993) pp.391-395.

[2] Hever, M.; Schröter, F.: *Modern steel - High performance material for high performance bridges*, 5th International Symposium on Steel Bridges, March 2003, Barcelona, pp. 80-91.

[3] Hubo, R.; Schröter, F.: *Thermomechanisch gewalzte Stähle - Hochleistungsprodukte für einen effizienten Stahlbau*, Bauingenieur 76, (2001), pp. 459-463.

[4] Dilg, C.; Kirsch, H.-J.; Streisselberger, A. Bauer, J.: *Accelerated cooling during plate production* , Steel Techn. Int. (1992) pp. 211 - 217.

[5] Sedlacek, G.; Eisel, H.; Paschen, M.; Feldmann, M.: *Untersuchungen zur Baubarkeit der Rheinbrücke A 44, Ilverich und zur Anwendung hochfester Stähle*, Stahlbau Vol. 71, No 6 (2002) pp. 423-428