Niobium Bearing Structural Steels
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APPLICATION OF NB IN TMCP STRUCTURAL STEEL PLATES WITH THICKNESS UP TO 120 MM

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Abstract

During recent years the thermo-mechanical controlled process (TMCP) was developed for structural steel plates with thickness up to 120 mm. Niobium as a micro-alloy in the steel enables to achieve a substantial grain refinement if the plate is rolled with a skilled combination of rolling steps at specific temperatures. As the very fine grained microstructure improves toughness and increases the yield strength, this TMCP process enables the required tensile properties with a leaner chemical composition. The consequence of a leaner chemical composition, especially of lower carbon content and lower carbon equivalents, is an improved weldability. Such steels permit a wide range of welding conditions producing sound welds and acceptable HAZ properties, a benefit for the fabricator which often turns out in substantial savings when replacing conventional structural steel by TMCP steel.

Thanks to the improved properties in parent metal and HAZ many impressive projects like offshore platforms, bridges, high rise buildings, foundations for offshore wind towers, were built from heavy TMCP rolled plates. This paper will explain the essentials of the production process, address some welding aspects and focus on reference projects which were recently realized with TMCP plates of Dillinger Hütte.

Introduction

In the last years, the production of structural steel plates has been required to meet more difficult demands. A lower ambient and service temperature leads to lower design and testing temperatures of the steel. Typical temperatures for the CTOD-test for applications in the North Sea decreased from -10°C to -40°C for other areas (Figure 1).

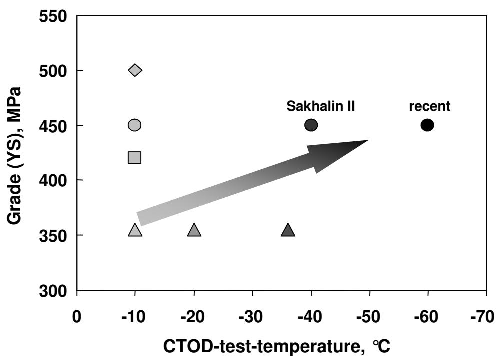

Figure 1. Development of technical requirements for offshore plates.

It is very important for the weight and the costs of a construction to save material - in other words to reduce the thickness of the plates by using a higher grade. For complex constructions the workability is an essential point. The aim is a design which reduces the carbon equivalent in order to reduce the preheating and interpass temperature during welding. For all these demands the TMCP process offers tailor-made solutions. But what has all this to do with Niobium?

Why using Niobium for TMCP-process

Niobium plays its most important role in the production of structural steels during austenite processing. Niobium delays recrystallization after deformation as a function of the temperature [1]. In the lower austenite region this leads to a complete suppression of recrystallization. Figure 2 shows this effect in comparison to Titanium and Vanadium as a function of the alloying content [2]. After rolling this effect leads to elongated austenite grains and therefore an enlarged number of nucleation sites for the γ–α-transformation. If the austenite does not recrystallize during or after deformation, the process is called thermomechanical process. The result will be a microstructure with very fine ferrite grains. Other effects of Niobium e.g. precipitation hardening of carbonitrides with block displacements in the atomic lattice and retardation of γ–α-transformation are described in several papers [1,3-6]. The effects of Nb exploited by TMCP cannot be utilized by a heat treatment alone.

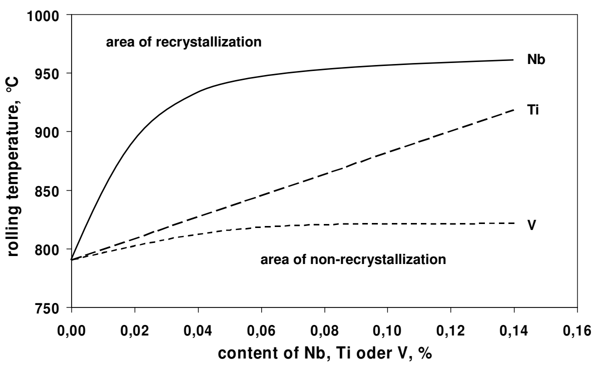

Figure 2. Effect of Nb, Ti and V on the minimum rolling temperature for austenite recrystallization [2].

The advantages of the TMCP-process

The rolling processes of the normalizing and some variants of TMCP processes are described in Figure 3a. Reheating, austenitization, homogenization and the dissolution of micro-alloying elements occur at a defined temperature range. For standard rolling after reheating of the slabs the rolling happens in the area of recrystallization of the austenite. After rolling at final rolling temperature (Tfr), the plates are cooled on air. The demanded properties are achieved after an additional heat treatment. The TMCP process makes use of the rolling in the no-recrystallization area caused by micro-alloying elements like Niobium. After pre-rolling (a stage of grain refinement with recrystallization) the next rolling stages are placed in the area of no recrystallization. The effect is pancaking of the austenite which leads to a very fine ferrite grain. Different TMCP-processes are possible. The last rolling passes can be in the two-phase-region (γ+α) with the effect of cold deformation of ferrite. Or, during γ–α-transformation an accelerated cooling with different final cooling temperatures (Tfc) and cooling rates can be applied. Figures 3b and c show the comparison of standard rolling (N: Normalizing process) and TM-processing variants: The processes, the yield strength and the different grain refinement of the microstructure. To get the same level of YS like the N-process a lower carbon equivalent Ceq is possible (Figure 4) or in other words: With the same Ceq higher level of YS is possible.

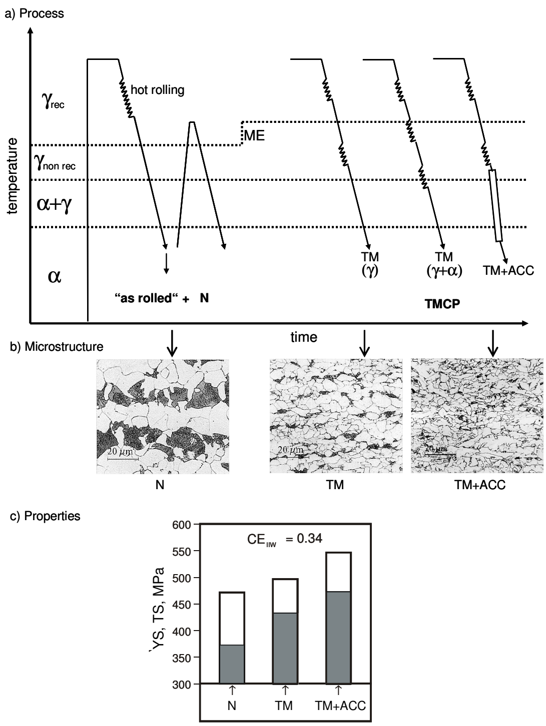

Figure 3. Process design types, microstructure and properties for Normalizing (N) and TMCP.

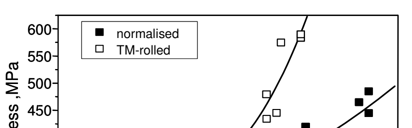

Figure 4. TMCP-steel – low alloying content.

Because of the finer grain size of the TMCP-process, not only the strength can be improved by TMCP. The toughness will also be increased. Figure 5 shows that the transition temperature will be lower and the upper shelf energy will be higher for the TMCP- in comparison to the N-process, but all this is well known. The much more interesting question is: how can you get from a design temperature of 0°C to a design temperature of -30°C or lower?

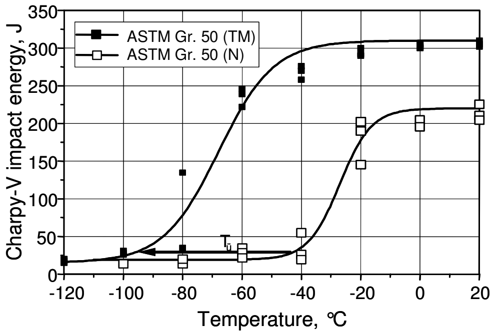

Figure 5. TMCP-steel – low alloying content.

Modern TMCP- process for difficult challenges

The design temperature decreased during the last years from -10°C (North Sea) to -40°C (Sakhalin and Kashagan). For the future for application in harsher environments we have to be prepared for design temperatures of -60°C. Last year Dillinger Hütte developed special steels in 75mm thickness. These steels have a yield strength above 450MPa, high impact values at -80°C (base material and HAZ), meet CTOD requirements at -60°C (in base material and HAZ) and a non ductile temperature (NDT) in the DWT-test lower -60°C [7].

These toughness requirements may be contradictory with other properties. But the whole properties become achievable in a complex combination of alloying and process techniques as a result of comprehensive development and investments. To fulfill such high demands on strength level - with TMCP up to grade S500 for structural steels - and low temperature toughness (CVN, CTOD and NDT) the use of a steel with very high cleanness is a stringent prerequisite. Dillinger Hütte is an integrated plant with coke making, blast furnaces, steel plant and two rolling mills (Dunkerque and Dillingen). In the secondary metallurgy almost 100% vacuum degassing can be performed. One of the continuous casters is the biggest vertical caster in the world [8], with a possible maximum slab thickness of 400mm. Therefore the maximum thickness of structural TMCP steel plates could be increased to 120mm [6].

The plates were produced with the above described TMCP-process up to a thickness of 120mm in the rolling mills with powerful high stands. Especially for thick plates, the potential of the high-power stands has to be exploited completely. Maximum possible reduction per pass improves the quality of the center of the plates. This is important for achieving good toughness in mid-thickness and through-thickness tensile test results. All steps like reheating, different rolling steps with defined start and final temperatures, the cooling and hot piling are monitored and controlled within very narrow production ranges.

For low temperature toughness the MULPIC (Multi-Purpose Interrupted Cooling) equipment has been developed in recent years to reach high cooling rates for the heavy ACC- and DQST- (Direct Quenching and Self-Tempering) processes (Figure 6) to ensure homogeneous properties with extremely fine grained microstructure [9-11]. During this development the microstructure changes from a ferrite-pearlite steel to a ferrite- bainite and martensite steel (Figure 7).

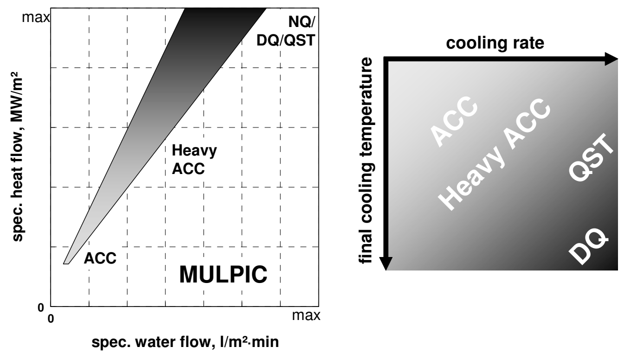

Figure 6. Cooling intensity as a result of water flow density and cooling variants [11].

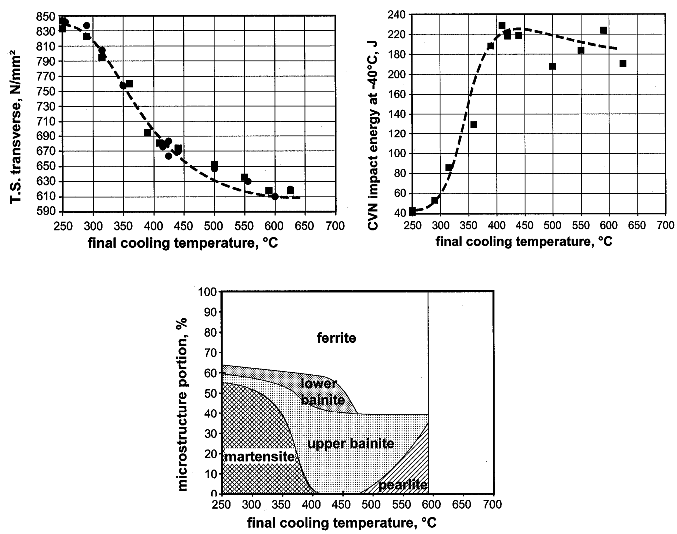

Figure 7. TMCP-steel – low alloying content [9,11].

Fabrication and weldability

Welding of TM-plates

For the fabricator the most significant advantage of TMCP plates compared to normalized ones of equal grade and thickness is their improved weldability. Hardness in the HAZ, the susceptibility to hydrogen assisted cold cracking and the toughness in the HAZ shall be considered.

HAZ hardness

The HAZ hardness of two steels of 460MPa yield strength is shown in Figure 8 versus the $t_{8/5}$ cooling time. For usual welding conditions resulting in $t_{8/5}$ times between 10s and 30s the hardness of the TMCP steel is well below 300HV. Due to the different chemical composition the TMCP steel is almost 100HV less hard than the normalized steel in the complete $t_{8/5}$ range. For very short cooling times and a microstructure mainly consisting of martensite, the hardness difference is only due to the different carbon content, because carbon governs the martensite hardness. In case of higher heat inputs the influence of the alloy content and micro-alloys becomes more pronounced. The higher HAZ hardness of a normalized steel leads to restrictions in the welding process if hardness limits e.g. 350 HV10 are specified.

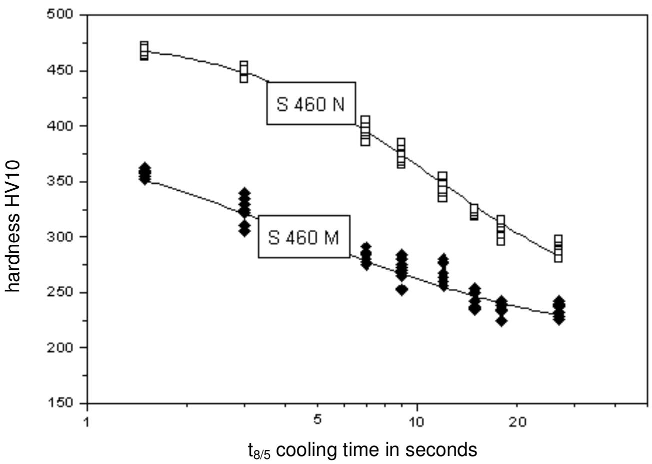

Figure 8. Bead on plate HAZ hardness in the coarsened grained zone for different cooling times – as welded condition.

Niobium is also a strong precipitation hardener. At the high temperatures close to the fusion line the initial Nb containing particles are dissolved and able to re-precipitate. The most important hardening effect caused by Niobium is observed for a PWHT in the range of 580°C for which numerous fine semi-coherent particles are formed.

Cold cracking and the necessary preheat temperature for welding

An important aspect for the fabricator of heavy structures of high strength steels is the prevention of hydrogen assisted cold cracking in the weld. Preheating and post-heating, the precautions against these defects, are rather time consuming and cost intensive and they are also difficult to be carried out and controlled on site. A comparison of recommended preheat as a function of the plate thickness for some typical combinations of heat inputs and hydrogen levels for the mentioned welding processes is shown in Figure 9.

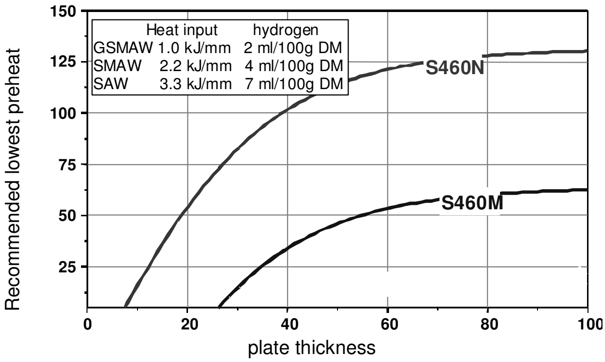

Figure 9. Calculated preheat temperatures as a function of plate thickness – moderately restraint weld.

The use of TMCP steel replacing normalised steel, allows an essential reduction of preheat temperatures and in many cases no preheating is required [12]. It is clear that the extension of welding without preheat is related to very low hydrogen input, hence on the appropriate welding consumable, good quality control in the shop and reliable welders.

Figure 10 compares applicable welding working ranges for a normalized steel S355J2+N and a TMCP-steel Dillimax 500ML with higher yield strength. The lower limit of the heat input is set to avoid hydrogen induced cold cracking, the upper limit of the heat input and interpass temperatures are introduced for gaining sufficient strength and toughness properties. The working range of the normalized steel is significantly restricted. The TMCP-steel has a wider working range resulting in the possibility to use highly efficient welding procedures.

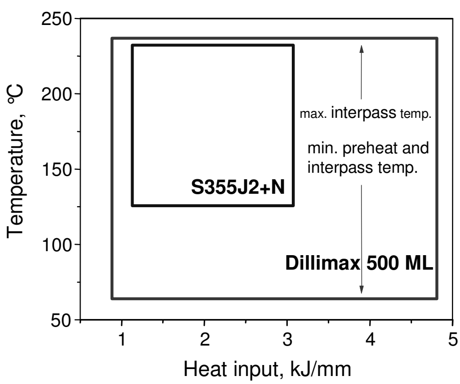

Figure 10. Welding: working ranges.

Toughness of the HAZ

For the steel qualification for offshore platforms the steel had to show sufficient HAZ toughness on different butt welds in the range from very low heat input of 0.8kJ/mm to high heat inputs of 4.5kJ/mm. Typical specifications for the North Sea require impact testing at

-40°C and CTOD testing at -10°C (see Figure 11). Additional impact transition curves of the HAZ of Dillimax 500ML are shown in Figure 12. Thanks to the low carbon and microalloying content the welds of our TMCP plates result in good impact toughness and allow a wide range of welding heat inputs without deterioration of the toughness. Under many conditions welded constructions built from TMCP plates need no PWHT because the as-welded condition is already sufficiently tough and HAZ hardness moderate.

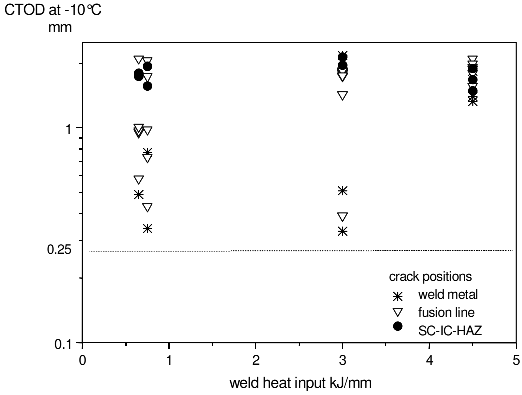

Figure 11. CTOD results on welded joints, full size BxB SENB specimens, a/W~0.5, through thickness notch, as welded condition, data from reference [13].

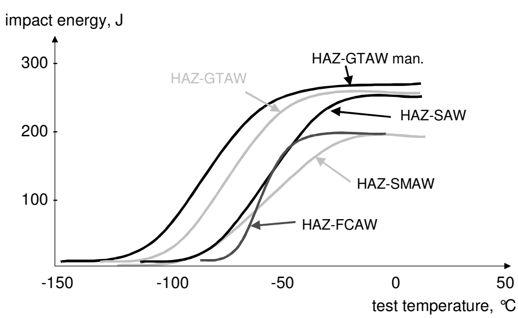

Figure 12. Impact transition curves on welded joints of Dillimax 500ML welded with different processes [14].

Application of Dillinger Hütte TMCP plates

In the following sections some examples of the application of structural steel plates produced with the TMCP process are given. All grades were microalloyed with Nb contents between 0.015 and 0.040 %.

Grade S460ML for Ilverich Bridge (Germany): A special pylon design was required with a low height as the bridge is near the flight-paths of the Düsseldorf airport. The high forces in the pylon heads demanded Grade S460ML (EN 10025) in thickness up to 100mm. The design derived an extraordinary toughness criterion of 27J at -80°C at quarter thickness position. A CuNiMoNb steel with a CE_{IIW} of about 0.39% was selected to produce the plates. The toughness requirements were comfortably met (Figure 13).

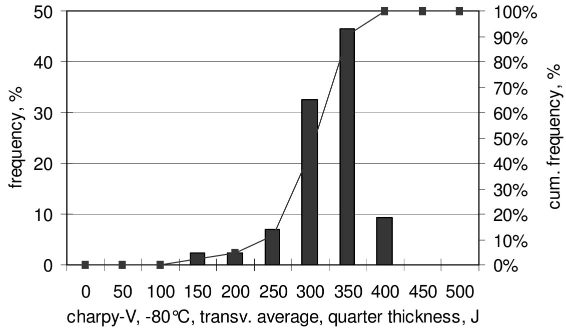

Figure 13. Toughness at -80 °C on plates in S460ML for Ilverich bridge, CuNiMoNb steel with CE_{IIW} ~ 0.39%, thickness 80 – 100mm.

Grade S500M3z for Valhall Offshore platform: The application of Grade S500M3z according to NORSOK standard (YS: 500-580MPa, TS: 600–750MPa, CVN (transverse, mid-thickness) at 40°C≥60J (each individual test ≥42J)) in parts of the topside of the offshore platform resulted in a notable weight reduction in comparison with Grade S420M3z. The main cost benefit of that weight reduction was achieved as it enabled installation of the topside with a single lift operation. A steel with a CE_{IIW} of about 0.42% combined with a DQST process (Direct Quenching and Self Tempering) was applied to produce plates in thicknesses up to 80mm. With that concept adequate toughness properties can be achieved even at mid thickness position (Figure 14).

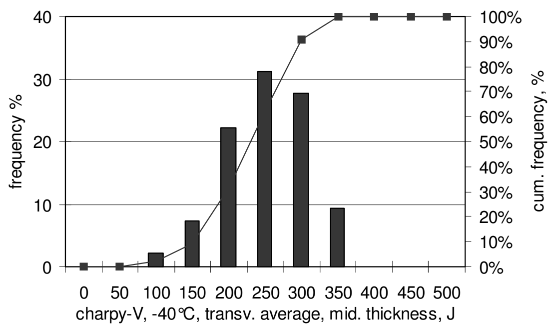

Figure 14. Toughness at -40°C at mid thickness position and transverse direction on plates in S500M3Z, steel with CE_{IIW} ~ 0.41%, thickness 40–80 mm.

Grade 450EMZ for Sakhalin II Offshore platforms: An extraordinary challenge was the production of plates for the Sakhalin II project. As a result of the harsh environment a toughness of 60J minimum was required at -60°C at mid thickness position in combination with CTOD requirement at -39°C. TMCP-route with a adequate alloying concept was applied for thicknesses up to 90mm. To meet the severe toughness requirement the Ni content was increased. The CE_{IIW} was about 0.43%. Figure 15 shows the toughness distribution curve for thicknesses between 60 and 80mm.

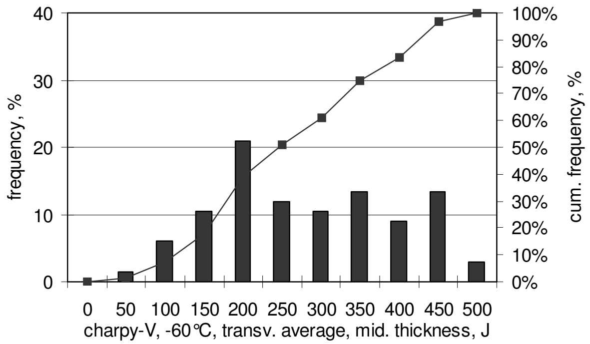

Figure 15. Toughness at -60°C on plates in 450EMZ for Sakhalin II, steel with CE_{IIW} ~ 0.43%, thickness 60-80mm.

Dillimax 500M/ML for hydro power application: For the Chinese hydropower plant LAXIWA the lower part of the penstocks was constructed by using Dillimax 500M/ML, a thermomechanical rolled steel with min. YS of 490MPa and min. TS of 610MPa. In total 3400t were delivered in thickness from 27mm up to 70mm. It was the first time that a thermomechanical rolled steel was used for penstocks. The most important issue for the application of Dillimax 500M/ML was the combination of excellent welding properties with the high tensile strength and the weight reduction of the construction. Figure 16 shows the tensile strength distribution for the delivered thickness range. Meanwhile Dillimax 500M/ML is also used for the construction and reconstruction of European hydropower plants (e.g. Cleuson Dixence (Switzerland), Pragnères (France)).

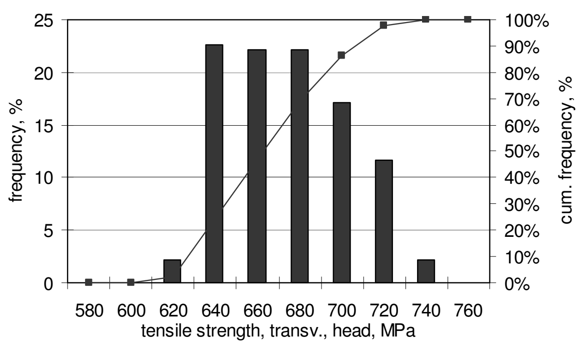

Figure 16. Tensile strength distribution on plates in Dillimax 500M/ML for Laxiwa, thickness 27–70mm.

S460M (EN 10025) for World Financial Center (WFC) Shanghai: Another example for the application of HSLA steel plates is the WFC high riser building in Shanghai. With 101 stories and a height of 492m WTC belongs to the highest buildings in the world. For special parts of the construction of the building a steel with good workability and a constant yield strength of min. 450MPa (Figure 17) was required. More than 7,700t of S460M in thickness up to 100mm were delivered in TMCP condition. The building was inaugurated in August 2008.

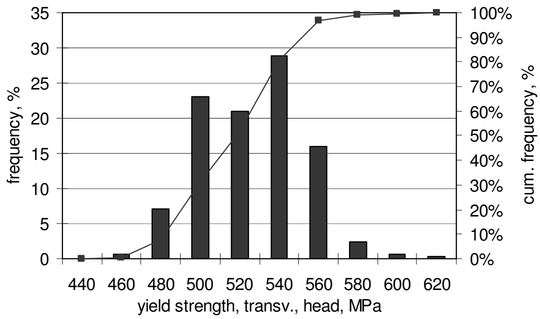

Figure 17. Yield strength distribution for plates in S460M for WFC-Shanghai, thickness 20-100mm.

S460M/ML for Viaduct de Millau (France): With a total height of 343m, a length of 2,460m and a roadway height of 270mm over the Tarn valley, the Millau Viaduct represents a new world record in bridge construction. Originally designed as a pre-stressed concrete bridge, a new draft as a multiple-cable-stayed bridge consisting of a steel bridge deck and towers, showed that not only the construction period could be shortened. The big advantages of using steel instead of concrete were a lighter and more slender bridge deck (weight of 36,000t compared to 120,000t for concrete), a reduced box girder height of 4.20m (lower wind exposure), minimization of the number of inclined tension cables and foundation work as well as a longer durability (120 years). All this led to a clear reduction of the overall project costs. Almost half the structure consists of high-strength fine-grained S460ML structural steel (18,000t, thickness 10-120mm). The special TMCP production route for this steel allowed the achievement of high strengths combined with excellent weldability.

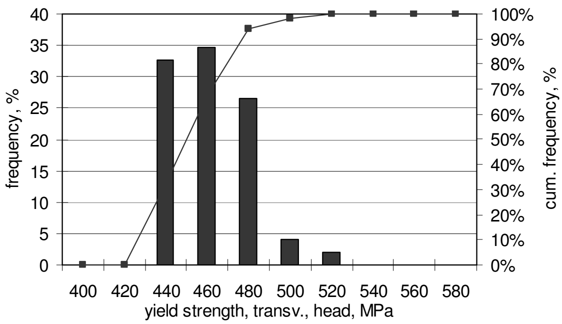

Figure 18. Yield strength distribution on plates in S460ML for Viaduct de Millau, thickness 100-120mm .

Figures 18 and 19 shows the distribution of YS and TS for plate thickness ≥100 to 120mm (requirements: YS≥430MPa (100mm) / ≥400MPa (120mm); TS: 510 – 680MPa (100mm) /

500 – 680MPa (120mm)). For these thicknesses a CuNiNb steel analysis with a CE_{IIW} of about 0.39% was used. The toughness requirements of -50°C in quarter thickness and longitudinal direction (≥27J (average)) were also safely met (Figure 20).

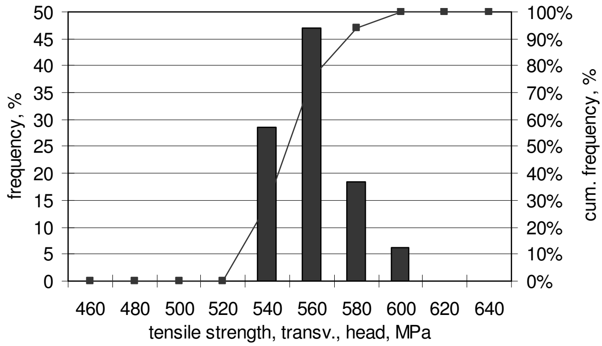

Figure 19. Tensile strength distribution on plates in S460ML for Viaduct de Millau, thickness 100 – 120mm.

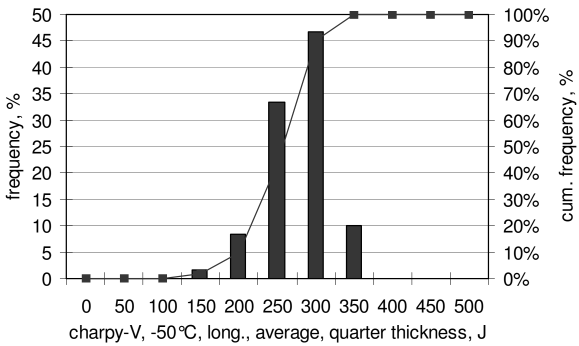

Figure 20. Toughness distribution at -50 °C on plates in S460ML for Viaduct de Millau, thickness 100 – 120mm.

Many other examples for the beneficial application of HSLA steels produced by TMCP can be given. Depending on the project requirements different tailor-made TMCP production routes for plate thickness up to 120mm can be chosen.

Conclusions

The paper has touched the recent development of design and production technologies for structural steel plates by TMCP. The effect of microalloying elements like niobium on the TMCP process has been explained. The complex property profile for high strength, toughness at lower temperatures, workability etc. become achievable in a complex combination of alloying and process techniques as a result of comprehensive development and investments at

Dillinger Hütte. Application examples have been presented. They cover a range of projects with challenging requirements in terms of plate dimensions and properties.

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