High strength steel for steel constructions

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ABSTRACT: The field of application for high strength steel reaches from offshore and hydropower constructions to ship- and bridgebuilding. Steels with very high strength (up to 1,100 MPa) are generally produced by a quenching and tempering process (Q+T). Extremely high strength is always associated with higher amounts of alloying elements and tends to result in higher hardenability which leads to a higher risk for brittle fracture and hydrogen induced cracking in welded constructions. In particular this is the case when the optimal processing parameters for welding are not used. Regarding the overall efficiency in steel constructions, the choice of a steel with moderate strength but excellent weldability can be an advantage. These properties can be achieved in a plate by using the thermomechanically controlled process (TMCP). The good weldability of this material allows the choice of efficient and cost-saving welding processes. This article describes the state of the art in production of high strength steels, especially an overview on the different delivery conditions is given. The processing properties of a thermomechanically rolled steel of 500 MPa minimum yield strength are presented in comparison with steels of other delivery conditions.

1 INTRODUCTION

Steel plates in today’s steel constructions have to fulfil increasing requirements. The technical requirements of modern steel constructions as well as the need for good handling during transportation and fabrication demand for higher strength steels. But these steels have to fulfil the desire for good processing properties also, especially concerning welding on site. This is the real challenge for modern steel producers.

Steels with very high strength (up to 1,100 MPa) are generally produced by a quenching and tempering process (Q+T). Extremely high strength is in most cases associated with higher amounts of alloying elements and a tendency to result in higher hardenability. This may lead to a higher risk for brittle fracture and - when used in welded structures - hydrogen induced cracking, in particular if the optimal processing parameters for welding are not applied. Due to that in constructional steelwork grades up to 690 MPa yield strength are reasonably used for special elements.

Regarding the overall efficiency in steel constructions the choice of steel with a more moderate strength but excellent weldability can be an advantage. These properties can be achieved in a plate by using the thermomechanically controlled process (TMCP). With this technique in connection with accelerated cooling (ACC) a yield strength of 500 MPa in plates up to 100 mm thickness is obtainable with the use of very few alloying elements. Excellent toughness values in the base material and in the heat affected zone of a welded joint are possible. Furthermore the good weldability of this material allows the choice of efficient and cost-saving welding processes.
This article tries to point out the basics in heavy plate production, especially the meaning of the different delivery conditions. On this footing, the processing properties of a TMCP-steel of 500 MPa minimum yield strength are outlined in comparison with a normalised and a quenched and tempered steel. The direct effect of the delivery condition on the processing properties gives the reader a clearer sight on this topic and helps to simplify the process of choosing the right steel for a specific application.

2 CHRONOLOGY AND PRODUCTION PROCESS

The evolution in steel production in the heavy plate sector over the last decades is determined on the one hand by the development of quenched and tempered steels with very high yield strengths (S690Q, S890Q, S960Q and S1100Q) and on the other hand by thermomechanically rolled steels with a more moderate yield strength, but higher toughness (S355M, S460M and S500M). The chronology of structural steels is illustrated in Figure 1.

![Chronology of structural steels](image)

A classical steel plate is produced in several successive steps. First the steel is produced in a steel mill and is casted either by a continuous or an ingot casting process to a slab. The slab is then rolled in a rolling mill with two aims:

- Forming the desired dimensions
- Improving the inner steel structure

After rolling a heat treatment takes place in order to adapt the microstructure to get the desired mechanical properties. Nevertheless the right chemical composition is essential for the mechanical properties and has to be adjusted during the steel production process in the steel mill before casting. There, desired alloying elements are added to the liquid phase and the content of harmful trace elements like phosphorous, sulphur, nitrogen and oxygen is abated. By applying secondary metallurgy, ladle refinement and vacuum degassing a high cleanness must be achieved, which is the base for high quality steel.

3 DELIVERY CONDITIONS

As already mentioned in Chapter 1 there are different delivery conditions: as rolled (AR), normalised (N), quenched and tempered (Q) and thermomechanically rolled (M). In Figure 2 the temperature-time diagrams of these conditions are given.

After heating at temperatures of about 1100 °C the rolling of the slab takes place in the austenitic state, a crystal structure that is stable at high temperatures. After that the plate cools on calm air and the “as rolled” condition (AR) is achieved (Process A in Figure 2).
Then, to get a more homogenous microstructure an additional heat treatment can be performed. The plate is reheated just above the ferrite-austenite transformation temperature (about 800 – 900 °C, depending on the carbon content) and is cooled on calm air again. By this treatment the steel transforms from ferrite and pearlite to austenite and back again. This leads to a refined microstructure of ferrite and pearlite, which is called the normalised condition (N). By normalising steel grades with moderate strength and toughness requirements up to S460N can be produced (Process A + B in Figure 2).

![Figure 2. Delivery Conditions](image)

The temperature-time-diagram for the quenching and tempering process is quite similar to the one for normalising (Process A + C in Figure 2). After hot rolling and cooling the plate is reheated above the transformation temperature, so that carbon can dissolve in austenite, but then cooling is not performed on calm air, but in water (quenching) or in another medium that cools fast enough, so that there is no time for the formation of ferrite and pearlite which needs a diffusion process. The carbon stays dissolved and at room temperature the microstructure mainly consists of martensite, a distorted structure that has a high strength but a low toughness. With an additional tempering process the crystal latter has the possibility to relax with the effect that strength decreases while toughness increases, so that a material with a satisfactory combination of tensile and toughness properties can be produced. The effect of the tempering on the mechanical properties is shown in Figure 3. Steels up to 1100 MPa yield strength and higher can be realised in quenched and tempered condition (Q + T).

![Figure 3. Influence of increasing tempering temperatures on the tensile properties (left) and on the Charpy V transition temperature (right) - S890QL, 60 mm](image)
Another way to get steel with high strength is to create a microstructure with an extremely fine grain. The smaller the grain size is, the higher are the tensile and toughness properties. The thermomechanical rolling (TM or TMCP) is a method to realise such a fine grained microstructure by a skilled combination of rolling steps at particular temperatures and a close temperature control (Processes D to G in Figure 2). The gain in strength obtained by the grain refinement allows reducing effectively the carbon and alloying content of the TM-steel compared to normalised steel of the same grade (Figure 4). The improved weldability that results from the leaner steel composition is a major advantage of TM-plates. The applied "rolling schedule" is individually designed, depending on the chemical composition, the plate thickness and the required strength and toughness properties. Some typical TM-processes are shown in Figure 2. Especially for thick plates an accelerated cooling (ACC) after the final rolling pass is beneficial for the achievement of the most suitable microstructure as it forces the transformation of the elongated austenite grains before recrystallisation can happen. For very thick plates and high strength steel grades a tempering process can be used after accelerated cooling.

![Figure 4. Attainable yield strength in dependence on the carbon equivalent CE](image)

Figure 4. Attainable yield strength in dependence on the carbon equivalent CE

Figure 5 shows microstructures of the different delivery conditions. It is easy to identify the typical microstructure of normalised steel which is dominated by ferrite and pearlite. A direct comparison with TMCP structures shows two main differences. First, there are less black areas, a result of the lower carbon content and second, the smaller grain size, which is smallest when ACC is performed. A completely different appearance has the quenched and tempered steel. The martensite that is formed by displacive transformation shows a acicular (needle-shaped) microstructure.

![Figure 5. Microstructures of various delivery conditions](image)

Figure 5. Microstructures of various delivery conditions
4 PROCESSING

The weldability of structural steels is of major interest for fabrication. In order to apply efficient welding procedures and also to ensure a high safety of the weld even after suboptimal welding conditions on site, steels with excellent weldability have several advantages.

![Figure 6. Calculated hardness in the coarse grained HAZ as a function of weld cooling time (t8/5) for some structural steels in the as welded condition text.](image)

The temperature-time cycles during welding have a significant effect on the mechanical properties of a welded joint. Generally the cooling time from 800°C to 500°C (t8/5) is chosen to characterise the cooling conditions of an individual weld pass for the weld metal and the corresponding heat affected zone (HAZ). Increasing heat input and interpass temperature result in slower cooling and longer cooling time t8/5. With the welding parameters and the joint geometry, t8/5 can be calculated (see EN 1011). Diagrams showing the hardness in the HAZ as a function of the t8/5 time can be used to compare the transformation characteristics for different steels (Figure 6). In general the typical shape of these curves can be divided into three zones:

- high hardness level at short cooling times (mainly martensitic microstructure),
- lower hardness at long cooling times (bainitic microstructure),
- transition zone at medium cooling time (mixed martensitic / bainitic microstructure).

![Figure 7. Charpy-V impact energy in the HAZ of S500M after welding](image)

However, it should also be taken into account that these diagrams represent single-pass welds only, whereas the conditions in real multi-pass welds are more complex due to the transformation and refinement of the initial microstructure by subsequent layers. Figure 6 shows that at short t8/5-times the high-strength steel S690Q has higher hardness values in the HAZ at than a S500M. Due to that, restrictions in the welding process of S690Q are necessary. In the HAZ of S500M the hardness does...
not exceed 320 HV10, even at very short cooling times. This results in rather low crack susceptibility. As described above, the low carbon and alloying content of TM-steels is the reason for this advantage.

The tendency of grain coarsening increases with higher heat input. This leads to a higher risk of poor ductility and bad brittle fracture behaviour in the heat affected zone. To avoid this, the heat input during welding and in connection with that the t8/5-time have to be limited by a maximum value. The Charpy-V impact values obtained in various positions in the heat affected zone of a 30 mm thick S500M butt-weld joint (SAW process, 3.5 kJ/mm) are shown in Figure 7. Test results in the as-welded condition are also compared with those after Post Weld Heat Treatment (580°C/4h).

Although the values are quite homogeneously distributed, the specimens taken from the root (lower subsurface) and plate centre position show slightly higher impact values due to the positive tempering effect of subsequent welding passes, which causes a refining of the microstructure. It is also clear, that the values determined at the fusion line, i.e. the coarse grained zone (CGHAZ), are somewhat lower than the values in a distance of 2 mm. A PWHT has only a minor influence on the toughness. To sum up it can be said that a toughness level of 50 J at –40°C can easily be fulfilled even for welding with a high heat input of 3.5 kJ/mm. That allows the fabricator to apply high performance welding techniques and to reduce working time.
interpass temperatures is set to gain sufficient tensile and toughness properties. It is obvious that the working range for high-strength plates (S690) is restricted in order to obtain sufficient strength values in the weld. The TM steel has by far the widest working range resulting in the possibility to use highly efficient welding procedures in high safety when welding in on site conditions has to be applied.

The behaviour after cold forming is simulated by artificial straining and ageing tests. Cold forming has an influence on the toughness of the steel and even more if the cold-formed area is heated as it occurs during welding. This is a matter of fact. Figure 9 shows Charpy-V-temperature-transition curves for S500M steel in the delivery condition as well as after 5% straining and artificial ageing at 250°C. Obviously the Charpy-V transition curve shifts to higher temperatures if cold forming is performed and even more after a further simulated ageing treatment. Despite these hard conditions, very good toughness levels can be reached which results in good formability.

5 APPLICATION

Originally TMCP-steels of 500 MPa minimum yield strength come from the offshore industry. On offshore platforms high safety is of immense importance. So it is not astonishing, that TMCP-steels are used for this kind of application. Figure 10 (left) shows the Valhall Platform in Norway. Here S500M was applied in a thickness up to 65 mm.

Figure 10. Valhall-Platform (left, Photo: Aker Kvaerner Norway), pumped storage power station (right, Photo: Voith Siemens Hydro)

Figure 10 (right) represents in section the typical structure of a pumped storage power station where water is stored in a upper basin. It is accelerated in conduits, so called penstocks, to use the kinetic energy to produce electricity with generators driven by turbines. The wall thickness of penstocks can amount to 60 – 80 mm or even more. The penstock is assembled of pipe sections that are produced by bending a plate around the transverse axis. These sections have to be welded together on site under severe conditions. Here thermomechanically rolled plates of the steel grade S500M are applied as an optimum compromise between a high yield strength and good processing properties.

But not only the energy sector counts on the advantages of high strength TMCP-steels. Also in constructional steelworks these steels become more and more popular.

Figure 11 (left) shows the first part of the Airbus-hangar on Frankfurt Airport. With a length of 180 m, respectively 170 m for the planned second part of the building that is not yet erected, and a depth of 120 m, the hangar is designed to enable the maintenance of five Airbus A380 at the same time. It was necessary to use a special girder construction to realise a span width of 180 m. For this construction tailor-made TMCP-steel was applied, a modified version of S460ML. The European standard EN 10025 specifies a reduction of the minimum guaranteed yield strength with increasing plate thickness. For this project minimum yield strength of 460 MPa was guaranteed even for 120
mm plate thickness (EN standard only demands 385 MPa). This was possible by the use of the steel design concept of a S500ML.

Figure 11. Airbus-Hangar Frankfurt (left, Photo: Lufthansa), WFC Shanghai (right, Photo: Mori Building)

The world financial center in Shanghai (Figure 11, right) was inaugurated on August 30, 2008. Designed in the nineties and originally intended to be the tallest building in the world, it is now China’s tallest building and the third highest in the world with 492 m and 101 floors. The building features a concrete core with four mega columns at the corners, linked to one another by truss belts and to the core by bracing elements. For this very special structure amongst others S460ML was applied in thicknesses up to 100 mm. A minimum yield strength of 450 MPa was demanded and could be guaranteed instead of 400 MPa according to the European standard by the use of the same concept as above.

6 CONCLUSION

The paper gave an overview of the different kinds of structural steels and their delivery conditions. The thermomechanical rolling has developed over the last years so that today plates with extraordinary toughness values and a yield strength class of a S500 in thicknesses up to 100 mm can be produced. The excellent weldability of these steels in connection with high safety in processing, especially in on site conditions, makes TM-steel more and more essential in steel constructions.

7 REFERENCES


