Welding and fatigue in high performance steel

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ABSTRACT: This articles summarizes the current state of the art in the production and application of high strength heavy steel plates for steel structures. By the thermomechanical rolling process steel plates with yield strength up to 500 MPa can be produced. These are also characterized by best fabrication properties. Therefore these products can be efficiently used in big steel structures. For special elements also high strength grades with yield strength up to 690 MPa are sometimes used which are produced by the quenching and tempering process. Typical application examples will be given.

1 INTRODUCTION

Steel – in particular heavy plates - is the most important input material for heavy steel structures. Therefore it is obvious that the improvement of the efficiency of steel products in design, fabrication and service life of a steel structure is a key element to develop also the efficiency of the steel structure.

One way of gaining a higher productivity is offered by the use of higher strength steel, which can be defined as a product with a yield strength higher than 355 MPa. Under special constructional circumstances such higher strength steel enables the designer to reduce cross-sections saving also considerable fabrication time and costs by smaller welds. Furthermore, also higher strength steels with a good structural safety in particular against brittle fracture and excellent fabrication properties (welding) already exist. However, the weak points of designing with higher strength steel such as fatigue or displacement restrictions will also be commented.

Higher strength plates can be produced by various production processes which also influence the final using and fabrication properties of the steel. Here, mostly the thermomechanical rolling process is applied for the production of higher strength plates as thereby also good fabrication and utilisation properties can be guaranteed. Such plates are today produced up to a yield strength of 500 MPa and have gained special attentiveness in large span landmark bridges. But also other fields of applications, such as industrial buildings or medium span bridges, can profit from these materials. Furthermore, some extra high-strength steel with a yield strength up to 690 MPa is sometimes used for special structural elements in bridges and buildings. These steels are produced by a quenching and tempering process.

It can be seen that the production process of heavy plates has fundamental impact on the fabrication properties of a steel product. Therefore, the various production techniques which exist today for heavy plates will be described first. Secondly, it will be explained how this influences the fabrication properties, in particular welding of these steels.

However, some peculiarities concerning design, especially fatigue design, have to be taken into account when constructing with high strength steel. Finally, it will be shown how these steels can successfully be applied for steel construction.

2 OVERVIEW ON PRODUCTION PROCESSES

Weldable structural steels are delivered in the conditions: normalised, quenched and tempered, and thermomechanical controlled rolled, schematically shown in Figure 1. Figure 2 allows to compare typical microstructures for the above mentioned supply conditions.

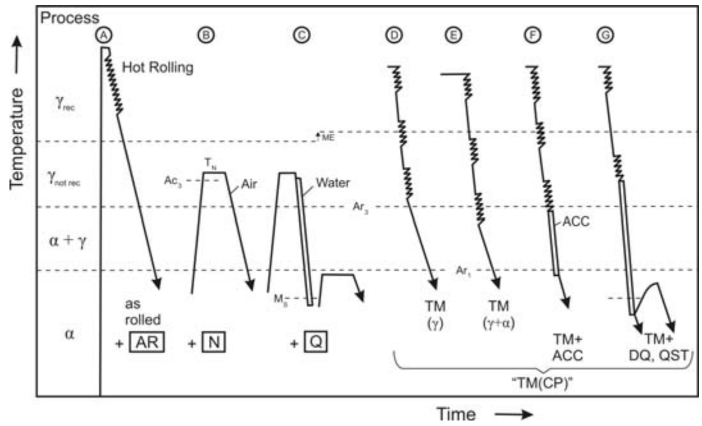

Figure 1 : Schematic temperature-time-procedures used in plate production: normalized (process A+B), quenched and tempered (process A+C) and different TMCP processes (D - G).

For steel grades of moderate strength and toughness requirements a classical hot rolling and **normalising** of the steel is sufficient to obtain the necessary mechanical values. By this process route weldable structural steels up to S460N are produced. Hot rolling is generally carried out at high temperatures above 950°C (process A in Figure 1). By reheating the hot rolled plates to some 900°C followed by free cooling in air a refined microstructure of ferrite and pearlite (process B in Figure 1) is obtained. However with this process a higher strength of steel plates is mostly related to higher alloying contents influencing weldability in a negative way.

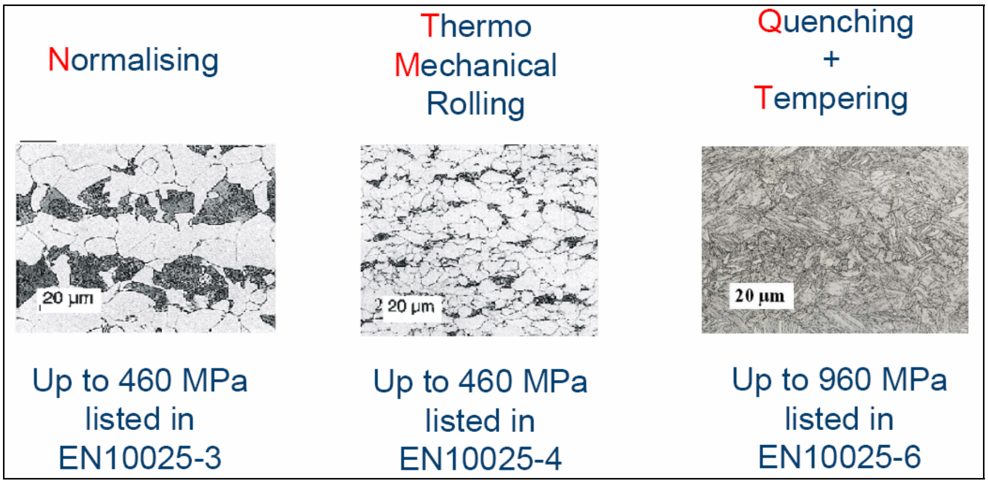

Figure 2 : Microstructure of conventional normalised steel (process B of Figure 1) compared to TMCP (process D), TMCP+ACC (process F) and Q+T steel (process C).

By **quenching and tempering** structural steels can reach a yield strength of up to 1,100 MPa. This heat treatment (process C in Figure 1) applied subsequent to hot rolling, consists of an austenitisation, followed by quenching and finally tempering.

The aim of **thermomechanical rolling** (TM or TMCP) is to create an extremely fine grained microstructure by a skilled combination of rolling steps at particular temperatures and a close temperature control. The gain in strength obtained by the grain refinement allows to reduce effectively the carbon and alloy content of the TM-steel compared to normalised steel of the same grade. The improved weldability that results from the leaner steel composition is a major advantage of TM-plates. Depending on the chemical composition, the required strength and toughness properties and the plate thickness the "rolling schedule" is individually designed. Some typical TM-processes are shown in Figure 1. Especially for thick plates an **accelerated cooling** 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 higher yield strength grades a tempering process can be used after the accelerated cooling.

TM-rolled plates with minimum yield strength values of 500 MPa were supplied up to 100 mm for hydropower, offshore platforms and special ships (Schütz & Schröter, 2005).

Figure 3 summarizes the historical development of higher strength steel grades during the last decades.

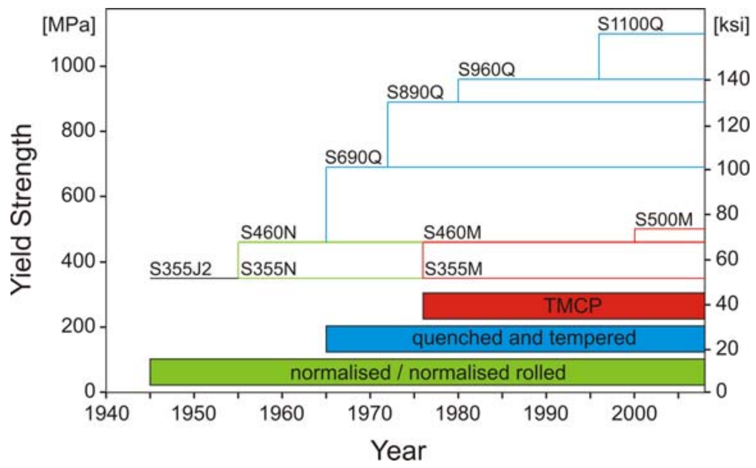

Figure 3 : Historical development of production processes for rolled steel products.

3 TMCP-ROLLED STEELS

The most significant advantage of TM-plates compared with conventional steel grades of the same thickness is their outstanding suitability for welding characterised by two main features: on the one hand, preheating of thicker TM-plates can be significantly reduced or omitted completely, which allows significant savings in fabrication time and costs. On the other hand, TM-plates exhibit high toughness values and low hardening values in the heat affected zone (HAZ) after welding (Schröter, 2004).

These effects are due to the very low alloying contents (in particular carbon contents) which can be reached by this special rolling process. Thus, Table 1 compares the typical alloying content of a conventional S355J2+N with that of a TM-steel of the same yield strength S355ML.

The table also indicates the values for the mostly used carbon equivalents, formulas which are used to judge the influence of the alloying elements on weldabilty. It can be seen that TMCP rolled steel shows much smaller carbon equivalents than normalized steel grades of the same yield strength.

Furthermore, TMCP rolled steel has an excellent toughness behavior. Figure 4 illustrates that the transition temperature between brittle and tough fracture behavior, which is often defined by the temperature, where a Charpy-V impact energy of 27 J is attained, can be significantly reduced by TMCP rolling in comparison to a conventional steel grade S355J2+N.

Table 1: Comparison of chemical compositions (according to the relevant standard and common production values for 50 mm plate thickness) between a normalized S355J2+N and a TMCP rolled S355ML
CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni+Cu)/15 ;
Pcm = C +Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B
CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40)

	S 355 J2+N		**S 355 ML**	
	acc. EN 10025-2	typ. analysis	acc. EN 10025-4	typ. analysis
C	≤ 0,22	0,17	≤ 0,14	0,08
Si	≤ 0,55	0,45	≤ 0,50	0,35
Mn	≤ 1,60	1,50	≤ 1,60	1,53
P	≤ 0,025	0,018	≤ 0,025	0,012
S	≤ 0,025	0,015	≤ 0,020	0,005
Nb	-	-	≤ 0,05	0,02
V	-	-	≤ 0,10	-
Mo	-	-	≤ 0,10	-
Ni	-	-	≤ 0,50	-
CE	≤ 0,47	0,42	≤ 0,40	0,34
Pcm		0,26		0,17
CET		0,32		0,24

Thus, a reserve is given in order to ensure also outstanding toughness properties in the heat affected zone of the weld. As an example Figure 5 shows the Charpy-V-temperature transition curve of an S355ML measured in the heat affected zone in distance of 2 mm to the fusion line. It can be seen that even at –50°C a good toughness level can be reached resulting in a high safety of the welded joint against brittle fracture. Furthermore, good toughness levels in the heat affected zone are a prerequisite for the application of welding processes with high heat input. Thus, also the efficiency of the welding process can be increased by using TMCP rolled material.

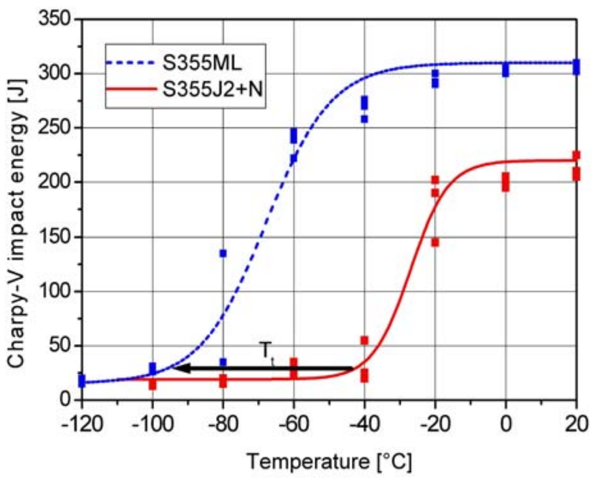

Figure 4 : Comparison of the Charpy-V-temperature transition curve for a conventional normalized steel S355J2+N and a TMCP rolled steel S355ML.

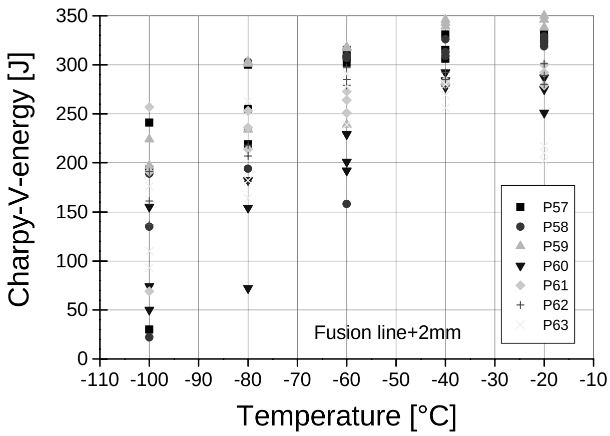

Figure 5 : Charpy-V-temperature transition curve in the heat affected zone of a S355ML after welding with submerged arc welding (3.0 kJ/mm).

Due to the higher carbon content and the risk of hydrogen-induced cracking a conventional S355J2+N in thickness above 30 mm is normally preheated prior to welding. Due to its low alloying content, TM-steel S355M is normally not preheated if EN 1011-2 is applied for the calculation of preheating temperatures.

The economic benefit of avoiding preheating is clear: A time- and money consuming step in the fabrication process of steel structures can be avoided and the production efficiency of the workshop be increased (Hever & Schröter, 2003). But this is not only a matter of economics. Also in terms of job safety avoiding preheating is a benefit. Welding in narrow box sections is the daily work of a welder on site. Reducing preheating temperatures results in better working conditions, better welding results and higher efficiency. Here TM-steel is the best choice.

One big advantage of TMCP rolling technique is that even higher strength grades can be produced by an appropriate heat treatment without considerably increasing the alloying content. Thus Figure 6 shows the mechanical properties of two steel plates of the same chemical compositions but with different treatments after rolling. By applying an especially harsh cooling – the so-called heavy accelerated cooling – the yield and ultimate strength of the steel plates can be increased without any change of the chemical composition.

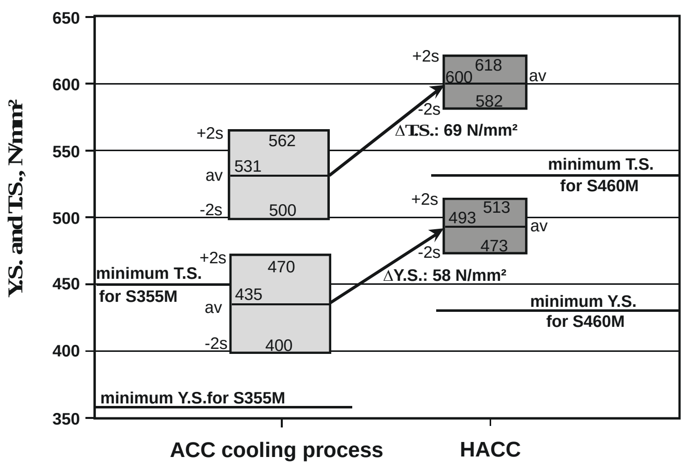

Figure 6 : Tensile strength and yield strength of two TMCP-rolled steel plates with the same chemical compositions but with different cooling speed after rolling.

Thus, even a steel with a minimum yield strength of 460 MPa can be produced with acceptable carbon equivalents for best weldability. For instance, an S460M steel shows a carbon equivalent of 0.40 – 0.42 % which may be lower than that for a conventional S355J2+N.

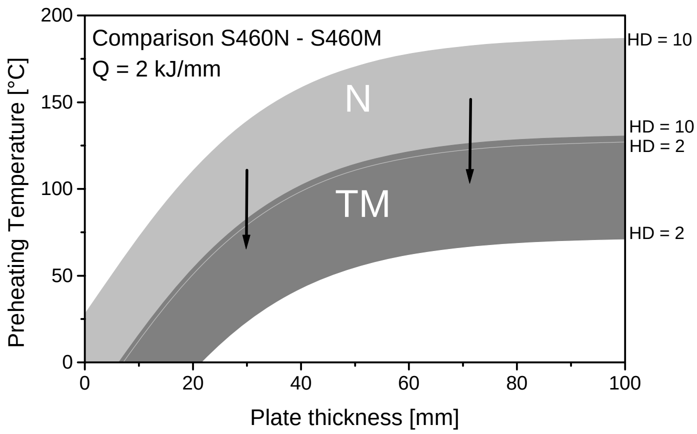

Figure 7 : Comparison of preheating temperatures according to EN 1011 between normalized steel S460N and higher strength steel S460M.

Thus, S460M enables the reduction of preheating temperatures in comparison to a conventional S460N. Furthermore, in most cases even for this higher-strength steel grade preheating can be omitted completely if special conditions on the welding process are fulfilled, as in particular the usage of low-hydrogen consumables (hydrogen content: HD) such as thoroughly dried basic electrodes. Figure 7 compares the necessary preheating temperatures for a S460M and S460N steel. Chapter 8 shows an example for the use of S460M: the Ilverich-Rhine bridge (Figure 20). Here welding inside of the narrow pylons on site was necessary. It was possible to avoid preheating by the choice of the TMCP-type of S460.

In order to reduce the danger of embrittlement in the heat-affected zone, steels unsusceptible to ageing are needed. The insusceptibility for ageing is shown on the material by notch impact tests on cold formed and artificially aged material. Figure 8 shows that the notch impact-temperature-transition curve moves towards higher temperatures when the steel is being aged, but relatively low transition temperatures can still be found even under this hard test conditions.

Further fabrication properties of TMCP-rolled steel can be found in Hanus & Hubo (1999) and Schröter (2004).

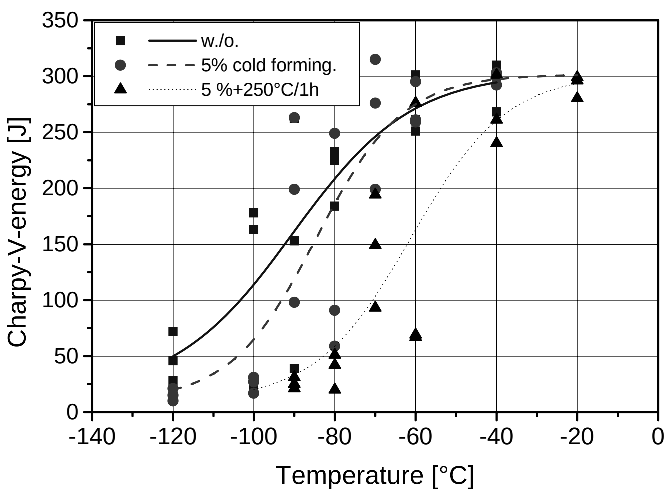

Figure 8 : Charpy-V temperature transition curves for an S500M steel without cold forming, with additional cold forming and cold forming with additional artificial ageing.

4 QUENCHED AND TEMPERED PLATES

Steels of 690 MPa yield became commercial about three decades ago. They were – like today - essentially produced by water quenching and tempering (QT). Nowadays QT-plates with a yield strength over 1,100 MPa have become commercial.

The aim of quenching and tempering is to produce a microstructure consisting mainly of tempered martensite. Some amounts of lower bainite are also acceptable. Quenching of high strength steels is performed after austenising at temperatures of 900-960°C. In order to suppress the formation of softer microstructure, essentially ferrite, during cooling an accelerated cooling is necessary. The fastest cooling is obtained by exposing the plate surfaces to a rapid water stream. By such an operation the very surface is cooled to a temperature below 300 °C within a few seconds. In the core of the plate cooling is considerably slower and the cooling rate decreases with increasing plate thickness. Therefore the alloying concept of thicker quenched and tempered plates has to be adapted to ensure sufficient hardening in the plate core.

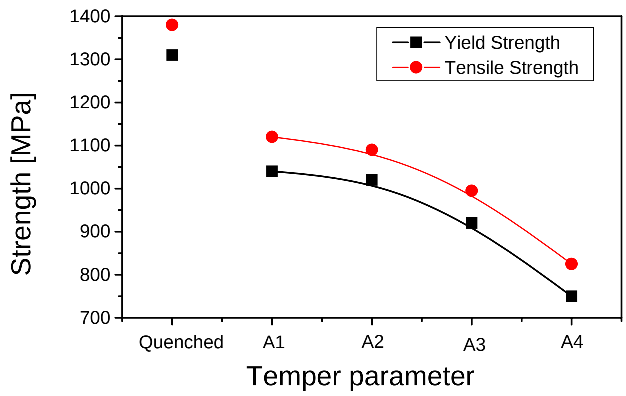

Figure 9 : Influence of increasing tempering temperatures on the tensile properties of S890QL in 60 mm thickness (Hanus, Schütz & Schütz, 2002).

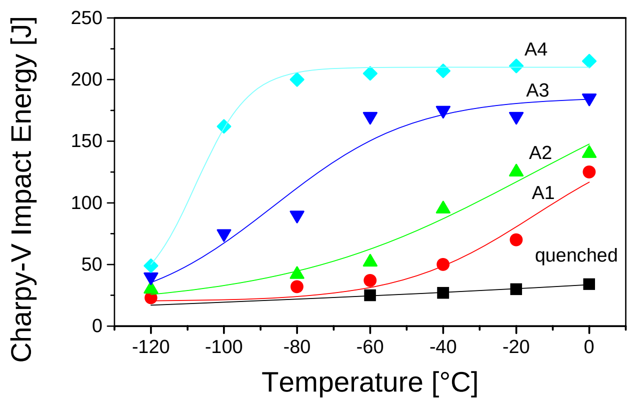

Figure 10 : Influence of increasing tempering temperatures on the Charpy impact temperature transition of S890QL steel.

If we consider the mechanical properties in the as quenched condition, the strength is considerably higher than required but the material is too brittle for most structural applications. A suitable tempering of the martensitic microstructure is necessary in order to get a satisfactory combination of tensile strength and toughness properties. By tempering the martensite, the supersaturation of carbon in the matrix is reduced by the precipitation of carbides leading to a relaxation in the atomistic scale. At the same heat treatment the high dislocation density associated with martensite formation is reduced. Both effects improve the toughness of the material. A

60 mm thick S890QL (EN 10025-6) is chosen for example that shows the influence of tempering on the properties. Figure 9 illustrates how the tensile properties are lowered with increasing temper parameter, Figure 10 the improvement of impact toughness, respectively.

The tempering conditions must be adapted to the particular chemical composition of the steel. The higher the toughness and strength requirements the closer gets the permitted range for the tempering conditions.

It has already been mentioned that the alloying compositions of quenched and tempered steel increases with growing plate thickness in order to ensure a sufficient hardening of the plate in the core region. Therefore, it is obvious that the carbon equivalent of a quenched and tempered steel increases with the plate thickness. An example is given by Table 2.

Table 2. Typical carbon equivalents of S690QL steel

Thickness [mm]	CE	CET [%]	Pcm
$t \leq 20$	0.42	0.30	0.26
$20 \leq t < 50$	0.59	0.37	0.31
$50 \leq t < 80$	0.66	0.39	0.32
$80 \leq t < 110$	0.72	0.41	0.34
$110 \leq t < 150$	0.79	0.44	0.35

Due to higher strength and carbon equivalents quenched and tempered steel grades of a yield strength of 690 MPa and more show a more sophisticated fabrication behavior than thermomechanically rolled steel grades.

5 WELDING

The temperature-time cycles during welding have a significant effect on the mechanical properties of a welded joint. It is understood, that the $t_{8/5}$-time is sufficient to describe the temperature-time characteristics. $t_{8/5}$ is the cooling time from 800°C to 500°C and describes the cooling conditions of an individual weld pass for the weld metal and the corresponding heat affected zone (HAZ). $t_{8/5}$ depends on the heat input during welding, the plate temperature (or interpass temperature), the shape factor (geometry) and on plate thickness if two dimensional heat flow occurs which is generally the case for thin plates.

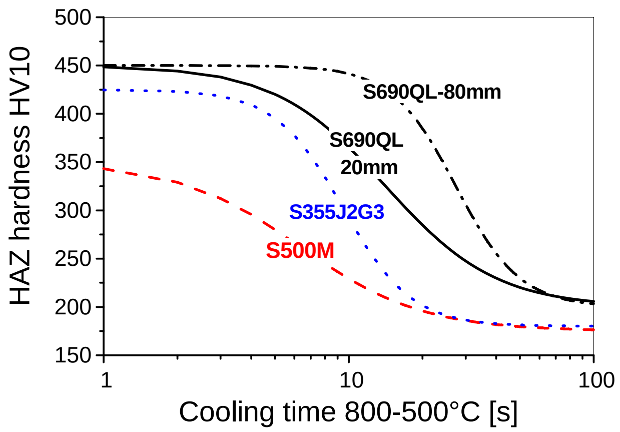

Figure 11 : Hardness in the coarse grained HAZ as a function of weld cooling time ($t_{8/5}$) for some structural steels in the as welded condition.

A limitation of the $t_{8/5}$-time to an upper and a lower value is necessary to obtain good mechanical properties in the weld and in the HAZ. The upper limit must not be exceeded in order to avoid an excessive harm of the mechanical properties by thermal load during welding. The lower limit avoids an excessive hardening in the HAZ, to which carbon steels tend when cooled quickly. In practice there are two variables to adjust $t_{8/5}$: heat input and interpass temperature, the welding parameters. Increasing heat input and interpass temperature leads to slower cooling and longer cooling times $t_{8/5.}$ Knowing the welding parameters and geometry $t_{8/5}$ can be calculated according to standard EN 1011-2.

To achieve satisfactory weld metal properties the welding parameters must be limited with increasing yield strength. For example acceptable properties for an S690 steel are normally obtained with cooling times between 5 s and 20 s. For lower cooling times the hardness of the heat affected zone may exceed limiting values with the risk of introducing cracks, see Figure 11. On the other hand, long cooling times result in poor strength and toughness values. The window between upper and lower admissible cooling times gets the smaller the higher the basic yield strength of the steel is. This is related to a narrowing of the window of welding parameters, from which heat input and preheating temperature can be chosen. Figure 12 shows the relation between the welding parameters and the recommended $t_{8/5}$-window for S690Q in 20 mm. The optimum working range lies between the blue and the green line. Parameters above the green line result in insufficient toughness and strength values, parameters below the blue line result in excessive hardening. But it can not be taken advantage of the whole working range between the two lines. There are also other parameters the working range depends on. The hydrogen content of the consumables H_2 [measured in ml/100 g] has a significant influence on the preheating temperature. In order to reduce the risk of hydrogen-induced cracking the preheating temperature must be increased with growing hydrogen content. According to EN 1011 the necessary preheating temperature T_p [in °C] under the condition of normal constraint conditions also depends on the heat input Q [in kJ/mm], the carbon equivalent CET and the plate thickness d [in mm]:

$$T_p = 697 \times CET + 160 \times \tanh\left(\frac{d}{35}\right) + 62 \times HD^{0.35} + (53 \times CET - 32) \times Q - 328$$

This formula results in the red line of Figure 12. Higher carbon equivalent CET, higher hydrogen content and higher plate thickness demand higher preheating temperatures and shift this curve to the right. This reduces the size of the working window. To avoid hydrogen induced cracking and excessive hardening as well and to obtain sufficient strength and toughness values, the welding parameters must lie in the grey area of Figure 12.

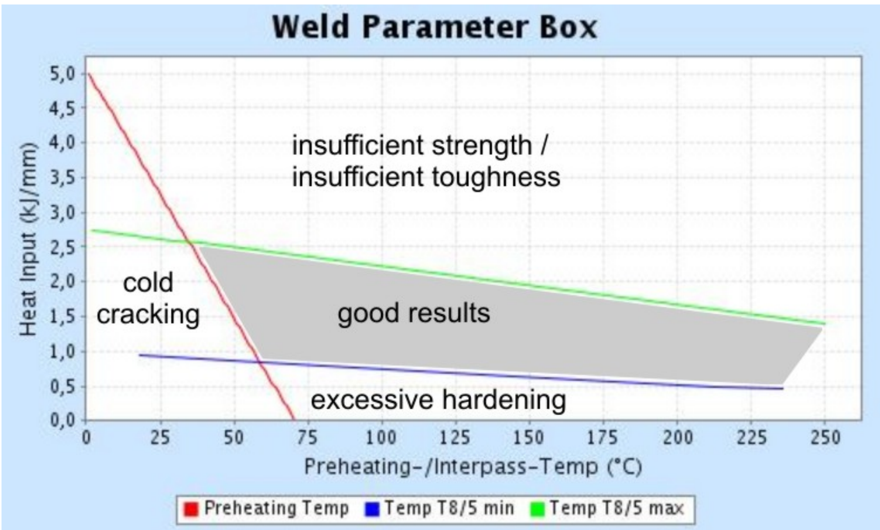

Figure 12 : Weld parameter box: S690Q, d = 20 mm, CET = 0,34, HD = 2 ml/100g

6 FATIGUE RESISTANCE

Fatigue contains two main processes: crack initiation and propagation. On sub-microscopic scale the dislocations (imperfections in the metal´s internal structure) are responsible for the crack initiation process. After a certain extend of load cycles the dislocations pile up and form small intrusions and extrusions in the surface that produce stress concentration and end up in a small crack. The duration of the crack initiation process depends on the yield strength of the material. The higher the yield strength, the longer this process and the better the fatigue behaviour. Therefore high strength steel has a better fatigue resistance than mild steel. This is true for a specimen with a polished surface without defects. For a notched sample things change. If the specimen is notched the crack propagation process dominates which mainly does not depend on the yield strength. Figure 13 shows the fatigue behaviour of steel samples with different yield strength and geometry. With increasing notch sharpness the fatigue resistance decreases. The independence of fatigue behaviour from the yield strength for notched samples is an important fact because welded structures show similar behaviour.

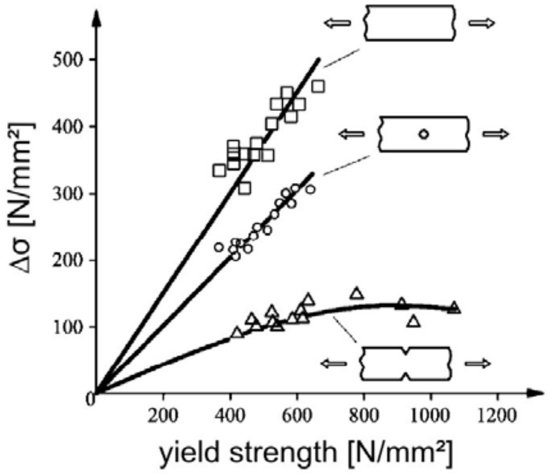

Figure 13 : Wöhler-chart (transverse stiffener, S460, R=0,1).

The fatigue resistance of welded structures limits the use of higher strength steel in dynamically loaded constructions. It is understood that the fatigue resistance of welded details performed under normal conditions is more or less the same for normal mild steel and for higher strength grades. So unfortunately the better fatigue behaviour of high strength steel cannot be used. Thus it can happen that the designer of steel structures cannot profit from the higher static strength of high-strength grades if the construction is dynamically loaded.

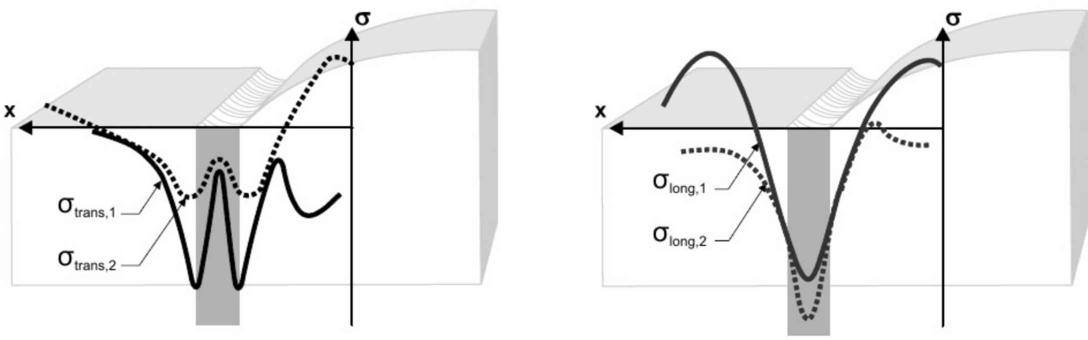

Figure 14 : residual stresses after post weld impact treatment

On the other hand it is also known that the fatigue resistance of high-strength steel can be improved by reducing the notch effect of the weld details. Apart form special precautions to perform high weld quality, this can be reached by special post-treatments of the weld.

In general these post-weld treatments are processes which reduce the notch effect of the weld details, such as the TIG dressing or a grinding of the weld. For instance the TIG dressing smoothens the weld notch by a further remelting of the transition zone between weld and base material.

But also post treatments, such as shoot peening and hammering, exist which introduce compression stresses in the transition zone between weld and base material. By these processes the transition zone is plastically deformed inducing compression stresses. Also smaller defects in the weld are removed. However, these processes are rarely used in steel construction due to high vibrations, noise and also poor reproducibility.

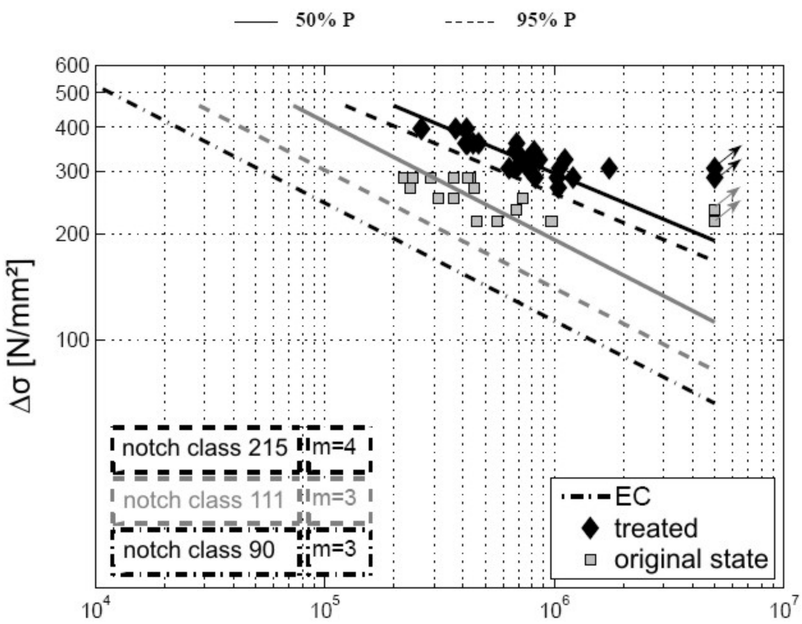

Figure 15 : S/N-curve, S690QL, R=0,1, with and without impact treatment

New high frequency processes represent an upcoming post-treatment technology which do not show these disadvantages. The detailed equipment technology is not part of this paper but in general the different available machines work in a high frequency range with hardened pins or bolts. The hammering bolts are moved along the weld toe and combine the two mayor effects of post treatment: Improving geometry by plastic deformation to reduce the notch effect and inducing compressive stresses which are beneficial for fatigue resistance. Figure 14 shows an typical example for the distribution of the residual stresses after post weld impact treatment as well as the effect on geometry.

These processes are under close investigation in several research projects. REFRESH (Research Report, 2009) is one of them. Figure 15 shows some selected results of fatigue tests performed in this study for various post treatments of the weld for S690QL. The dashed line shows the level where 5 %, the straight line where 50% of the specimens are assumed to have failed under a constant cyclic load. The R-value (ratio between lowest and highest) load is fixed at 0.1. The tests have been performed on MAG-welded butt joints.

Although the number of tests given in these charts is very limited, it can be clearly seen, that the fatigue resistance can be improved by the new post treatment processes. These results give the hope that the efficiency of dynamically loaded steel structures can be improved. It should be taken into account that the number of details for which the fatigue resistance is the determining factor in the design process, can be very small. Therefore, the improvement of the fatigue behavior in such local areas can increase significantly the efficiency of higher strength steel in the entire structure.

7 EXAMPLES

The benefits of using high strength steel in steel structures are clear: In comparison to normal strength steel the size of the cross section can be reduced resulting in

- a decrease of the dead weight of the structure, from which the substructure and the erection profit.
- reduced cross section of welded joints by which fabrication and inspection costs can be reduced and higher clearance heights under overpasses can be ensured.

For this reason higher strength steel are not only used for bigger landmark bridges but also for more convenient medium span bridges.

Figure 16 : Bridge in Zuid-Beveland (The Netherlands).

Figure 16 shows such a standard bridge, a bridge across a canal in Zuid Beveland, the southern part of the Netherlands. Here a girder construction of S460 was chosen in order to reduce the girder depth and to allow maximising the clearance height for the canal under the bridge.

As another example Figure 17 shows the bridge of Rémoulins in the South of France. For this continuous twin-girder construction with span lengths of 47, 66 and 51 m a combination of TM-steels S355ML and S460ML was used. The high-strength S460ML was especially applied in the highly stressed pier region of the girders to reduce the maximum thickness. So only a maximum thickness of 80 mm instead of 120 mm (Figure 18) for the solution purely in S355ML was necessary resulting in weight reduction and an easier fabrication and erection procedure. Moreover, thanks to the choice of TM-material, fabrication costs could be additionally reduced by the avoiding of preheating. In total a weight reduction of more than 8 % could be obtained by using this special combination of materials.

Figure 17 : Rémoulins Bridge in France.

A typical example for the application of S690Q-steel in medium span bridges in Germany is displayed in Figure 19. Here a composite bridge across the freight railroad centre in Ingolstadt with span lengths of 24 + 3*30 + 24 m is shown. The cross section consists of two 1.2 m-high plated girders in a distance of 7 m, cross beams in a distance of 7.50 m and a cantilevered concrete deck cast in-situ in a rhythm of 15 m. Here S690Q was applied for the connection between the girder and the piers formed by concrete filled steel tubes of 600 mm diameter. The 70 mm-thick lamella of S690 was welded to the girder to form a bending-stiff connection. Thus, a very efficient alternative for bearings was created.

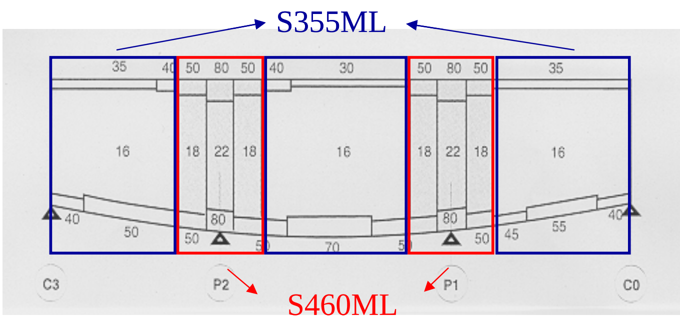

Figure 18 : The Rémoulins Bridge, Longitudinal section.

However, the real domain of high-strength steel grades such as S460M is still the construction of bigger bridges such as the new Rhine-bridge in the north of Düsseldorf (Germany), which was opened for traffic middle of 2002 (Sedlacek, Eisel, Paschen & Feldmann, 2002). 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, see Figure 20. Therefore, the high forces arising in the pylon heads could only be solved by selecting the high-strength steel S460ML for these structural elements. Even plate thickness' up to 100 mm have been used for the central parts of the pylon heads.

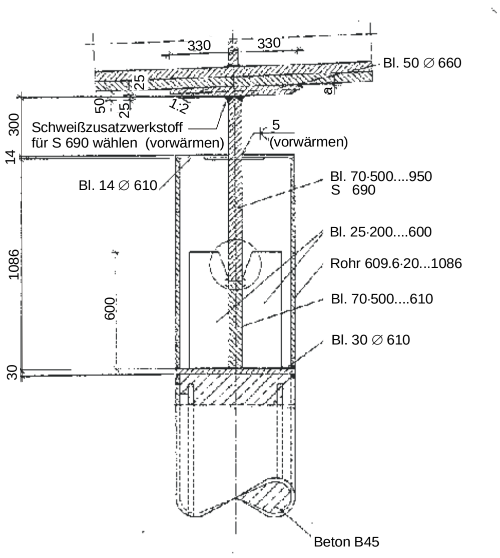

Figure 19 : Pier and pier-girder connection of a bridge near Ingolstadt.

The most impressing example for the use of higher strength grades in bridgebuilding is shown by Figure 21. The Millau Viaduct in the South of France, which was opened end of 2004, is the highest bridge in the world by a total height of 343 m, a deck height of up to 270 m and a length of 2,460 m. The total weight of steel plates used for this extraordinary bridge is

43,000 t, among this 18,000 t of S460M. Apart from the pylons this steel grade was used for wider parts of the box girder in particular to reduce the weight during the incremental launching process and to optimize the thickness of welded elements for efficient and quick construction.

Figure 20 : The Ilverich Bridge in Düsseldorf-North (Germany)

An example for the application of higher strength steel grades in building structures is shown in Figure 22. The structure shown there forms a part of the Sony-Center in Berlin. This truss structure is fixed on three columns and holds the lower apartment building which hangs above the facade of an ancient hotel. The truss girders consist of welded box sections made of S460 in thickness' up to 110 mm. Due to the high stresses the nods between flanges and diagonals are built of lamella packages made of S690.

Figure 21 : The Millau Viaduct after completion

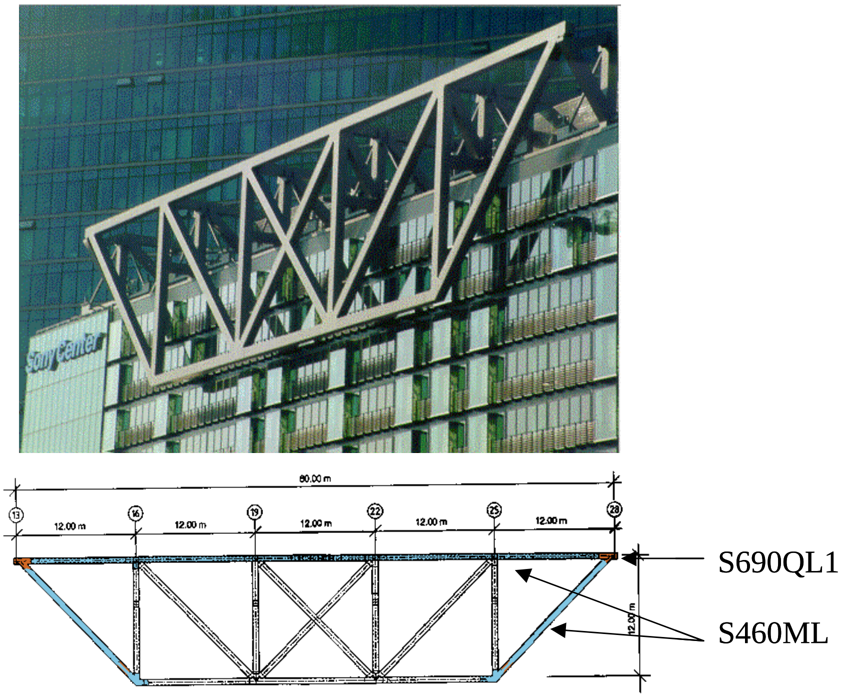

Figure 22 : Building F of the Sony-Center, Berlin.

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

Figure 23 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).

Figure 23 : Airbus-Hangar Frankfurt (Photo: Lufthansa)

The world financial center in Shanghai (Figure 24) 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.

Figure 24 : World Financial Center Shanghai (Photo: Mori Building)

8 CONCLUSION

This article highlights the recent developments made by the steel industry in order to supply steel products for more efficient steel buildings.

However, other obstacles may exist in the single countries which may hinder the utilisation of these efficient steel products, for instance ancient building regulations penalising or even forbidding the use of these products. However, countries with such an attitude can strongly benefit from experiences made in other countries, where these "new" materials are already introduced widely in the market. Thus, for instance in Norway, more than half of all steel bridges use high-strength TM-rolled steel, whereas these steels are still used only in special constructions in Germany. This simple example shows that steel structure design in a particular country cannot only profit form "new" material offered - it can also profit from the experiences made with these materials in other countries. Let's use it to built more efficient, safe and also beautiful steel structures.

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