Recent Developments in Heavy Plate Production for Modern Steel Bridges

T. Lehnert & F. Schröter
Dillinger Hütte, Werkstr. 1, 66763 Dillingen, Germany

ABSTRACT: Today’s bridge construction is characterized by highest demands on efficiency, quality and sustainability. Facing this, fabricators are longing for developments which can support them to reduce cost, time or environmental impact of a bridge. Even though modern heavy plate production is far developed, quality producer invest consequently to further improve their steels. These smaller developments can nevertheless lead to major advantages in bridge design and construction, e.g. thermomechanically rolling (TM) is a well-known process from the linepipe industry, which due to its superior properties gains increasingly ground in steel construction. With TM-plates even the upcoming challenging demands on weldability of high strength plates can be served. Beyond that, nowadays the maximum plate thickness for TM-plates is increased to 150 mm. Other recent developments are the combination of thermomechanically rolling with weathering properties to overcome the problem of worse weldability for higher strength weathering steel or the so-called longitudinally profiled plates.

1 INTRODUCTION

Being highly cost efficient while maintaining the necessary quality and safety can be considered as the main challenge in modern steel bridge construction. Beside this, nowadays also sustainability gains more and more importance, as often life cycle costs or environmental impact of steel structures are taken into account in evaluating different design concepts. As this ecological aspect is quite new it is addressed by many research groups, e.g. the project SBRI – Sustainable Steel-Composite Bridges in Built Environment (Kuhlmann & Maier 2011). Due to its unlimited recyclability steel as such is already the ideal choice for a sustainable material in construction. This general advantage concerning a sustainable resource input can be furthermore fostered by the cost and energy reduction possibilities modern steel concepts provide in steel construction. Therefore the steel making industry has continuously developed more sophisticated steel grades to meet the arising economic and ecologic requirements (Hever & Schröter 2003, Schröter 2004). Thermomechanically (TM) rolling, for example, is a well-known process used for many years in line-pipe industry. Over the past years such TM-plates have gained more and more ground in the steel construction sector due to their superior processing properties. The following paper will shortly present some new developments in the field of TM rolling (e.g. extended thickness, higher strength weathering steels). Benefits as well as the potential in reducing cost and energy consumption in fabrication, assembly and transportation will be discussed. A second special product for bridge construction are the longitudinally profiled plates, so-called LP-plates. By their uniquely adjustable thickness profile they allow significant weight reductions and fatigue improvements in a bridge construction. New feasibilities can make their application even more efficient.

2 PRODUCTION OF THERMOMECHANICALLY ROLLED PLATES

While classical hot rolling (Process A in Fig.1) is mainly used to shape and homogenize a heavy plate, thermomechanical rolling (Process D-G in Fig.1) furthermore leads to an improvement of the mechanical properties of the steel plates by its rolling process. It can be defined as a rolling procedure where the temperature and time course during rolling are precisely controlled and adjusted to the chemical composition of the steel. Thermomechanical rolling basically consists of up to four process steps:

1. Heating of slabs to its predetermined rolling temperature
2. Rolling: following a given pass list where the last rolling pass takes place in the tempera-

ture range of non-recrystallizing austenite or in the two phase region of ferrite and austenite.

3. Cooling: After rolling the steel is cooled down to a definite temperature depending on the targeted steel grade. To do so, different cooling methods can be used: air cooling (D and E in Fig. 1), accelerated cooling (F) or direct quenching (G).
4. If necessary additional heat treatment (Tempering)

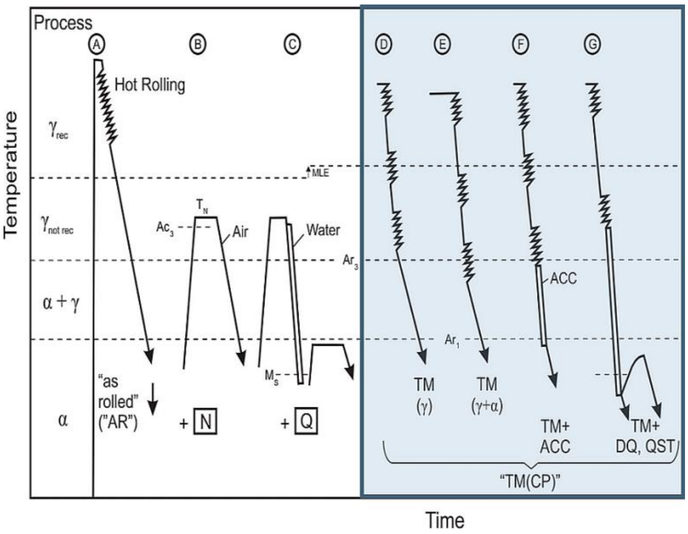

Figure 1. Schematic temperature-time-procedures used in heavy plate production (Schröter 2004).

All the steps of this complex rolling procedure target an extreme grain refinement in the microstructure of the steel plate. As described by the Hall-Petch relation such a refined grain has a positive influence on strength as well as on toughness of the steel. This structure-related gain in strength obtained by grain refinement allows reducing effectively the carbon and alloy content of a TM-steel compared to a normalized steel of the same grade.

Figure 2 shows the grain refining effect of thermomechanical rolling. Typical steel grades obtained by this rolling method are S355M/ML or S460M/ML according to EN 10025-4 or ASTM A1066 Gr.65.

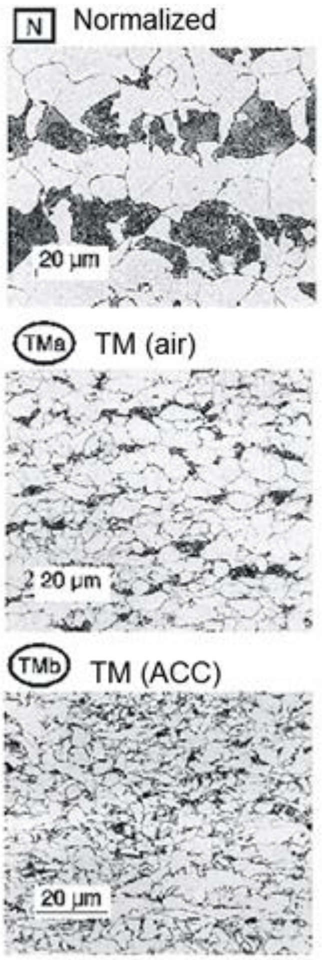

Figure 2. Effect of thermomechanical rolling on the grain size for normalized steel (N), thermo¬mechanically rolled steel cooled on air (TMa), as well as accelerated cooled (TMb).

3 GENERAL BENEFITS OF TM- PLATES ON COST AND SUSTAINABILITY

There are different ways the fabricator as well as the engineer of a steel bridge can profit from using thermomechanically rolled steels:

1. Transition from "normalized" to "thermomechanically rolled" steels in the same strength range (e.g. S355N ⇨ S355M)
2. Transition to higher strength while maintaining a very good weldability
   (e.g. S355N ⇨ S460M)

3.1 *Exchanging N with M in the same strength range*

As already stated thermomechanically rolled plates need less carbon and alloying material compared to its normalized equivalent to achieve the same strength (Fig. 3). Their low alloying contents are therefore the basis for the major advantage of TM-steels, their excellent weldability. The significantly improved weldability of TM-steels can be verified when comparing the carbon equivalent CET, a common measure of weldability, for a typical normalized S355J2+N with the one of a thermomechanically rolled S355ML (Table 1). CET was computed with Eq. 1 (Uwer & Höhne 1991).

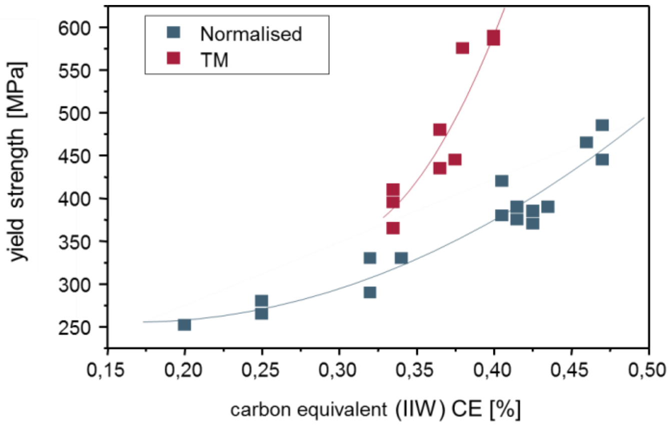

Figure 3. Yield strength as a function of alloying, expressed by the carbon equivalent CE (IIW).

Table 1. Typical carbon equivalent values for typical S355J2+N and S355ML

Steel grade	CET	CE (IIW)
S355J2+N	0.30	0.42
S355ML	0.24	0.36

$$CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40 \qquad (1)$$

The carbon equivalent CET allows the determination of the necessary preheating temperature Tp for welding, taking into account the avoidance of hydrogen-induced cold-cracking (Uwer & Wegmann 1996). According to EN 1011-2 the preheating temperature Tp is given by: (with hydrogen content in welding consumable HD [ml/100g], heat input Q[kJ/mm] and plate thickness t[mm]).

$$T_p = 697 \times CET + 160 \times \tanh\left(\frac{d}{35}\right) + 62 \times HD^{0.35} + (53 \times CET - 32) \times Q - 328 \qquad (2)$$

Due to the considerably reduced CET for TM-steels one can significantly decrease or even omit the preheating by using appropriate welding consumables (with low diffusible hydrogen content) also for higher strength steels and large plate thickness (see Fig. 4).

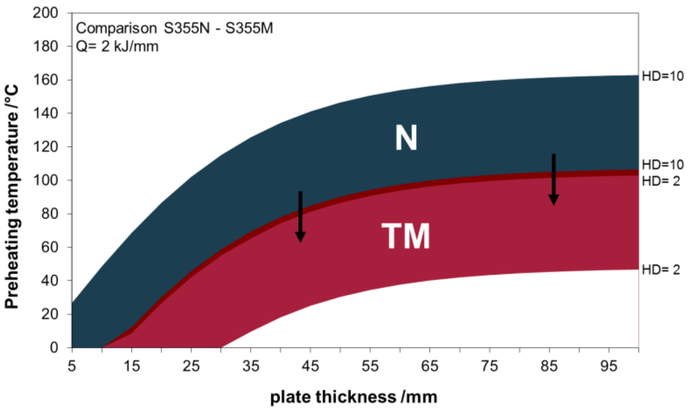

Figure 4. Reduction of recommended preheating temperature for TM-steels.

The achievable savings on the fabrication time (no time for cooling down/heating up, shorter setup times) as well as on the energy consumption during assembly enable a higher cost-effectiveness and improved resource management. An additional benefit of reduced preheating concerns job safety for welders, as it clearly facilitates welding in constricted rooms, e.g. inside box girders (Fig.5).


© Donges SteelTec GmbH

Figure 5. The reduction or even elimination of preheating makes working under constricted conditions much easier

Figure 6 gives an example where the fabricator had benefits from the usage of a thermomechanically rolled S355 steel, namely S355M/ML.

Figure 6. Ennëus-Heerma Bridge in the Netherlands with around 900 t S355M/ML

3.2 *Transition to higher strength grade*

Even though modern steel production methods enable steel grades with yield strength up to 1300 MPa, in bridge building the usage is mostly limited to steel grades up to 690 MPa (Samuelsson & Schröter 2005). To achieve such "higher" strength steel grades (with yield strength > 355 MPa) different procedures are possible:

1. Alloying: higher carbon equivalents and therefore decreased weldability
2. Thermomechanical rolling: excellent weldability, mainly up to 500 MPa
3. Quenching and Tempering: mostly up to 690 MPa in bridge building

The big advantage of using thermomechanically rolling as a production route for achieving higher strength steel grades is the remaining excellent weldability, while the other processes tend to an increased carbon equivalent and by that to a reduced weldability.

Figure 7. Higher strength thermomechanically rolled steel (S460ML) in bridge construction, Øresund Bridge, Danmark

With their increased strength – while simultaneously being sufficiently weldable – these thermomechanically rolled high strength steels allow notable material savings in fabrication and assembly (Willms 2008). If comparing for example the rated values for S355 and S460 (f_y = 315 MPa at 100 mm plate thickness to f_y = 430 MPa at 73 mm plate thickness), the change towards a higher strength steel allows a plate thickness reduction of around 30 % (not taking into account fatigue effects which are depending on the exact construction detail) (Fig. 8).

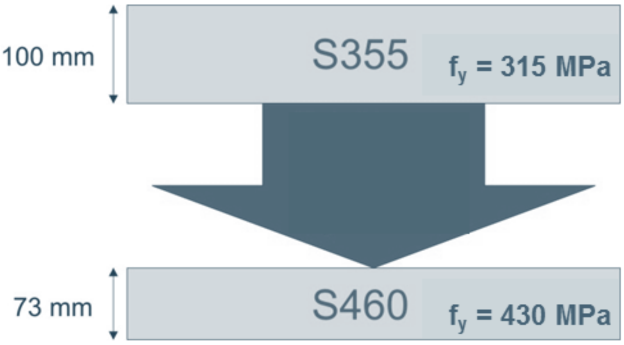

Figure 8. Possible reduction of plate thickness when using higher strength steel leads to savings in material consumption

Beside the reduced material amount these reduced cross sections impact the cost and eco-balance of a construction in multiple ways. First, the lower component weight enables bigger assembly units and thereby faster assembly plus optimized transportation. The hence lowered transport energy expenses (for example less truck transport) add a relevant sustainable aspect to the high economic efficiency of high strength steels in bridge building.

Furthermore, the thinner steel plates lead to a considerable reduction of weld seam volume. Due to the geometrical situation the weld seam volume is a quadratic function of the plate thickness and therefore the enabled savings in weld material and heating energy are disproportionately high with decreasing plate thickness (Fig. 9).

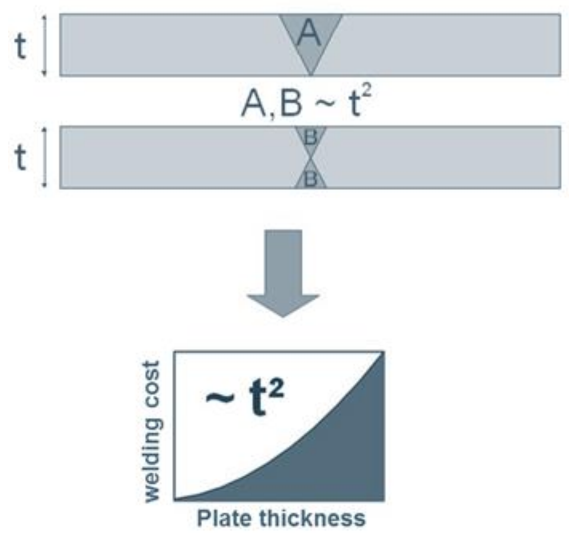

Figure 9. Realizable cost savings in welding dependent on plate thickness

A reduction of welding time as well as testing time complete the economic advantages associated with high strength thermomechanically rolled steel (e.g. S460ML in Figure 7).

4 NEWEST DEVELOPMENTS IN TM-PLATES

4.1 *TM - Plates up to 150 mm plate thickness*

To achieve the beneficial properties of TM plates a minimum degree of thickness deformation between the slab and the final heavy plate is of crucial importance. Given that, the maximal thickness for TM rolling is mainly limited by the availability of strong rolling forces as well as of semi-finished steel products with appropriate product thickness. Therefore to date the advantages of thermomechanically rolling were only available for plate thickness up to 120 mm. Thus EN 10025-4, as standard for TM plates in steel constructions, has defined such steels also only up to a thickness of 120 mm. Nevertheless, newest developments in steel manufacturing, e.g. very thick slabs from continuous casting, are now able to push this production-driven limit for another 30 mm. Hence, nowadays TM steel plates up to 460 MPa can be produced with plate thickness up to 150 mm. In order to allow maximum usability in bridge constructions these thick TM-plates fulfill the same mechanical requirements as a 120 mm thick plate according to EN 10025-4 (Table 2).

Table 2. Mechanical properties for 150 mm thick S355M/ML

Plate thickness t [mm]	Min. yield strength R_{eH} [MPa]	Min. tensile strength R_m [MPa]
$t \leq 16$	355	470 - 630
$16 < t \leq 40$	345	
$40 < t \leq 63$	335	450 - 610
$63 < t \leq 100$	325	440 - 600
$100 < t \leq 120$	320	430 - 590
$120 < t \leq 140$	320	430 - 590

For the S355ML, these so far thickest TM-plates in the world are now also certified by Germanischer Lloyd as well as approved by the German building authority (DiBT) up to 140 mm.

Especially the offshore wind industry, which generally needs thick and heavy plates with outstanding weldability to meet the designated efficiency goals by using fast welding processes, will profit from this new development in thermomechanical rolling.

4.2 *Higher Strength Weathering Steel*

The upcoming sustainability discussions in steel constructions, especially in bridge constructions, led to an increased interest in weathering steel solutions in certain parts of Europe.

In order to achieve such weathering properties (e.g. according to ASTM A709 or EN 10025-5) certain amounts of the alloying elements Copper, Chromium and Nickel (the minimum values are given in the respective standards) need to be alloyed to the steel. During first corrosion, these alloying elements form a homogeneous oxidic protection layer (Patina) on the steel surface which significantly decelerates the further atmospheric corrosion of the steel.

Even though these alloying elements lead to higher steel prices at a first glance, the omission of a separate corrosion protection layer can justify its usage economically as wells as environmentally. Especially the reduced maintenance efforts (e.g. no need for regular repainting) positively influence the life cycle costs of a construction with weathering steel. However, the usage of weathering steel in steel construction has certain restrictions and special care in the construction design is necessary, e.g. the construction needs to be designed in a way to prevent standing water on the steel surface. In other words this steel type needs a steady alternation between being wet and completely dried off again.

Several guidelines on how to design with weathering steels are available (e.g. DASt-Ri 007 in Germany).

Nevertheless, weathering steels are today of great interest and a challenging newly upcoming desire from bridge designers is a higher strength weathering steel with yield strength of 460 MPa and a still good weldability. Such a steel grade will combine the benefits of weathering resistance behavior with the ones coming from higher strength steel. But as the minimum content of alloying elements for the corrosion protection itself increases the carbon equivalents, the carbon equivalents of weathering steels are generally higher than the ones of normal constructional steels. The same relation applies for higher strength steels (see Table 3). Therefore a higher strength weathering steel produced by classical routes, e.g. normalizing, suffers from a very high carbon equivalent.

Table 3**:** Typical carbon equivalent values for 50 mm thick plates of different steel grades

Steel grade	CET
S355J2+N	0.30
S355J2W+N (normalized)	0.32
S460N	0.31
S460"W" (TM rolled)	0.28

Weather-resistant (S355J2+N → S355J2W+N)

⇨ CET ↑ (Weldability ↓)

Higher Strength (S355J2+N → S460N)

⇨ CET ↑ (Weldability ↓)

Thermomechanically rolling offers therefore an ideal solution to this metallurgical dilemma and somewhat attenuates these disadvantages. It can significantly enhance the weldability of weathering steels by its facility to allow reduced carbon equivalents. Such a thermomechanically rolled higher strength weathering steel (ASTM A709M HPS485W) was for example successfully used in the Haliç Metro Bridge in Istanbul, Turkey (Fig. 10). Even though the European standard for weathering steel (EN 10025-5) does so far not define a higher strength weathering steel, some heavy plate producers offer already branded steels with this property combination.

Figure 10. Higher strength weathering steel (A709M HPS485W) in bridge construction. Haliç Metro Bridge in Istanbul, Turkey

5 LONGITUDINALLY PROFILED PLATES

Another interesting product of the steel making industry is the longitudinally profiled (LP) plate. By perfect control of the rolling parameters the thickness over the length of the plate can be varied to a certain extent and a thickness profile can be obtained (Richter & Schmackpfeffer 1988). Figure 11 gives an overview of the possible profile types. Newest developments for LP plates allow now slopes of up to 10 mm/m. These new possibilities offer a greater freedom to the engineering in choosing the plate profile desired for various applications, e.g. bridges.

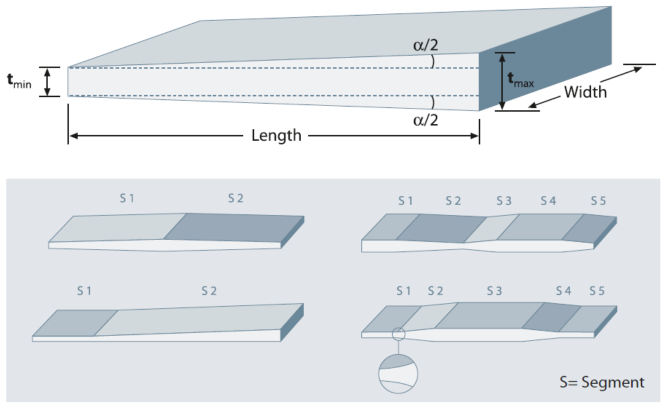

Figure 11. Overview of possible profiles for longitudinally profiled plates (LP plates)

Similar to the high strength steels the economic and ecologic benefit of this special type of steel plates lies mainly in a material weight reduction. The tunable plate thickness gives the opportunity to save excess material in regions where the thickness is not needed from static calculations. Given that the usage of LP plates can offer a cheaper solution by representing less excess material and less welding costs. This consideration implies only the fabrication cost and is not involving the inherent reduction of transportation cost and energy which is associated with such a lower component weight, as already stated before.

6 CONCLUSIONS

The steel making industry can significantly support the economic efficiency of a steel bridge by developing and refining modern steel concepts. Mainly the potential savings are associated with a reduction of fabrication time (faster welding processes, less time for preheating or transportation) or also with reduced energy and material consumption (weight reduction). Therefore positive effects on the environment are immanent. This combination of effects can help the steel fabricators reaching the ambitious goals of high profitability, safety and sustainability in modern bridge construction.

7 REFERENCES

Kuhlmann U., Maier P. Sustainability assessment to Steel-Composite Bridges. Proceedings of the International Workshop on Eurocode 4-2, Composite Bridges, Stockholm, Sweden, 2011.

Hever M., Schröter F. Modern steel – High performance material for high performance bridges. 5th International Symposium on Steel Bridges, Barcelona, Spain, 2003.

Schröter F. Steels for modern steel construction and offshore applications. 10th Nordic Steel Construction Conference, Copenhagen, Danmark, 2004.

Uwer D, Höhne H. Charakterisierung des Kaltrißverhaltens von Stählen beim Schweißen. Schweißen und Schneiden 1991; 43 (4):195 – 199

Uwer D, Wegmann H. Anwendung des Kohlenstoffäquivalents CET zur Berechnung von Mindestvorwärmtemperaturen für das kaltrisssichere Schweißen von Baustählen, DVS-Jahrbuch Schweißtechnik 1996; 96:46 - 55

Samuelsson A, Schröter F. High performance steels in Europe. Use and Application of High-Performance Steels for Steel Structures. Structural Engineering Documents, Zurich, 2005

Willms R. High strength steels in steel construction: Application and processing. Proceedings of the 5th European Conference on Steel and Composite Structures, EUROSTEEL 2008, Graz, Austria

Richter K, Schmackpfeffer H (1988) Herstellung von LP-Blechen und deren Verwendung im Brückenbau. Stahlbau 1988; 57 (2):33-38