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HOW MODERN STEEL DEVELOPMENTS CAN HELP OPTIMIZING COST AND SUSTAINABILITY OF BRIDGE CONSTRUCTIONS

T.Lehnert[1] and F. Schroeter[2]

ABSTRACT

The current economic situation, characterized by high requirements on cost as well as resource efficiency, puts strong pressure on the fabricators of infrastructure projects, e.g. bridges. These arising needs on efficiency and lower cost in fabrication, while simultaneously maintaining the safety and structural design requirements of bridges, are more than challenging. But in addition to these financial aspects, also life-cycle cost, sustainability and environmental impact are progressively becoming a major issue in the building sector and make great demands on the constructor, fabricator as well as on material. On the material side, the high recyclability of steel fits very well to such sustainable constructions and therefore it leads to steel being the favourable solution in sustainable bridge building.

The steel making industry is continuously trying to support the fabricator following these economic and ecologic challenges by developing more and more sophisticated steel. This leads on one hand to improved material as such and additionally cuts down on the cost and energy consumption of the subsequent processing steps in fabrication. Thermomechanically rolled higher strength steels serve as a good example for such an economical consumption of raw material. With its excellent weldability and outstanding toughness properties, the application of such higher strength steel grades can significantly reduce the statically claimed plate thickness in a certain construction aspect. Beside reduced general material costs this concurrently causes reduced transport energy as well as transport cost.

The presented report will show some of these modern steel developments and its bridge applications (e.g. thermomechanically rolled steels, high strength steels, longitudinally profiled plates, weathering steels or thick plates (thickness t > 80 mm)) as well as it will demonstrate the prospects these modern steels offer in reducing the cost of a steel construction and simultaneously its environmental impact, mainly by lowering the energy consumption of its fabrication.

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How Modern Steel Developments Can Help Optimizing Cost and Sustainability of Bridge Constructions

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The current economic situation, characterized by high requirements on cost as well as resource efficiency, puts strong pressure on the fabricators of infrastructure projects, e.g. bridges. These arising needs on efficiency and lower cost in fabrication, while simultaneously maintaining the safety and structural design requirements of bridges, are more than challenging. But in addition to these financial aspects, also life-cycle cost, sustainability and environmental impact are progressively becoming a major issue in the building sector and make great demands on the constructor, fabricator as well as on material. On the material side, the high recyclability of steel fits very well to such sustainable constructions and therefore it leads to steel being the favourable solution in sustainable bridge building.

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Introduction

Being highly cost efficient while maintaining the necessary quality and safety can be considered as the main challenge in modern steel construction. Beside this, nowadays also sustainability gains more and more importance, as often life cycle costs of bridges are considered in evaluating different design concepts. This ecological aspect is quite new and therefore addressed by many research groups, e.g. the project SBRI – Sustainable Steel-Composite Bridges in Built Environment [1]. Steel is due to its unlimited recyclability as such 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. The

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steel making industry has continuously developed more sophisticated steel grades to meet the arising economic and ecologic requirements [2, 3]. The following paper will shortly present some of these developments (thermomechanical rolling, high strength steels, longitudinally profiled plates as well as weathering steels). Benefits and their potential in reducing cost as well as energy consumption in fabrication, assembly and transportation will be discussed.

Modern Steel Concepts and Potential Benefits

Thermomechanically Rolled Plates

Production

In contrast to classical rolling processes thermomechanical (TM) rolling is not only used to shape and homogenize the heavy plate, but as well to achieve the desired material property combination. It can be defined as a rolling procedure where the temperature and time course during rolling is precisely controlled and adjusted to the chemical composition of the steel. Fig. 1 illustrates the different rolling procedures in heavy plate production. Basically thermomechanical rolling consists of three process steps:

- Slab heating to its selected rolling temperature
- Rolling: following a given pass list where the last rolling pass takes place in the temperature range of non-recrystallizing austenite or in the two phase region of ferrite and austenite.
- 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).
- If necessary additional heat treatment (Tempering)

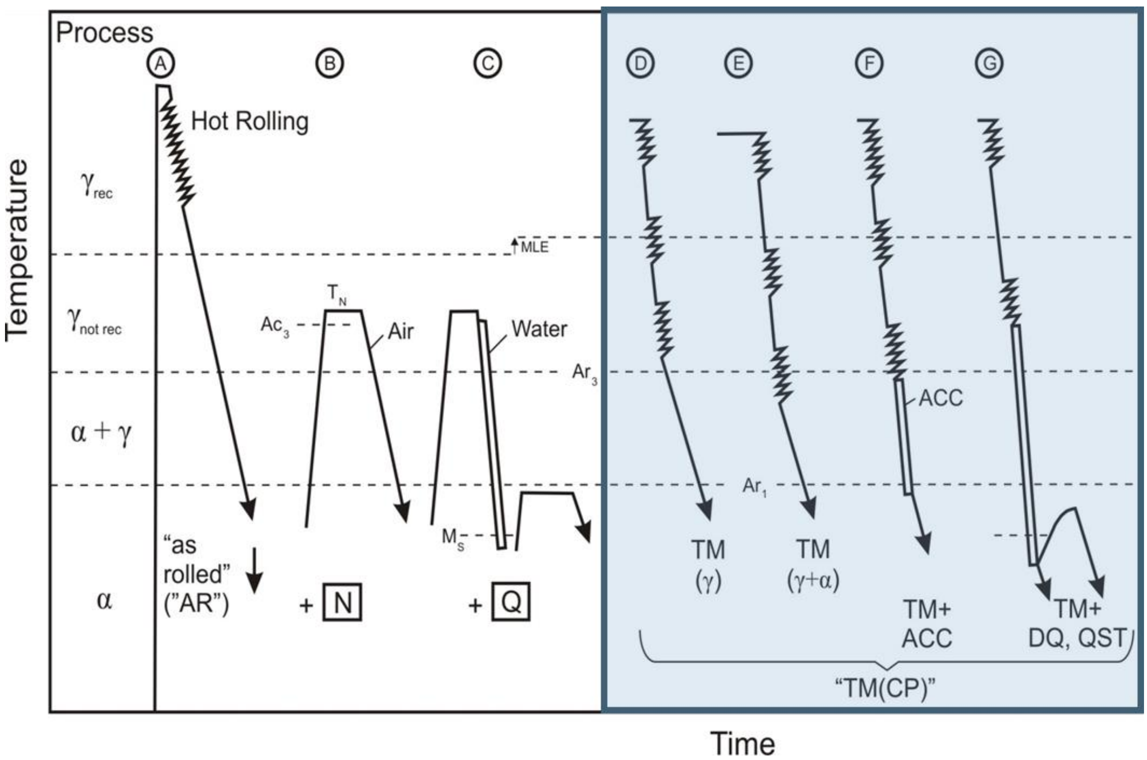

Figure 1. Schematic temperature-time-procedures used in heavy plate production [3]

The outstanding property of this complex rolling procedure is the 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 gain in strength obtained by the grain refinement allows reducing effectively the carbon and alloy content of the TM-steel compared to normalized steels of the same grade.
Fig. 2 shows this 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.

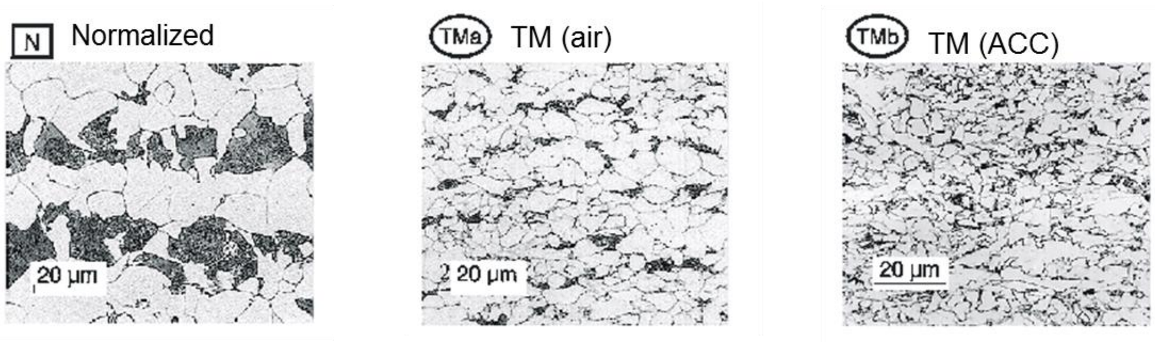

Figure 2. Effect of thermomechanical rolling on the grain size for normalized steel (N), thermomechanically rolled steel cooled on air (TMa), as well as accelerated cooled (TMb).

Benefits on cost and sustainability

As already stated thermomechanically rolled plates need less carbon and alloying material compared to its normalized equivalent to achieve the same strength (Fig. 3). This low alloying leads to 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 [4].

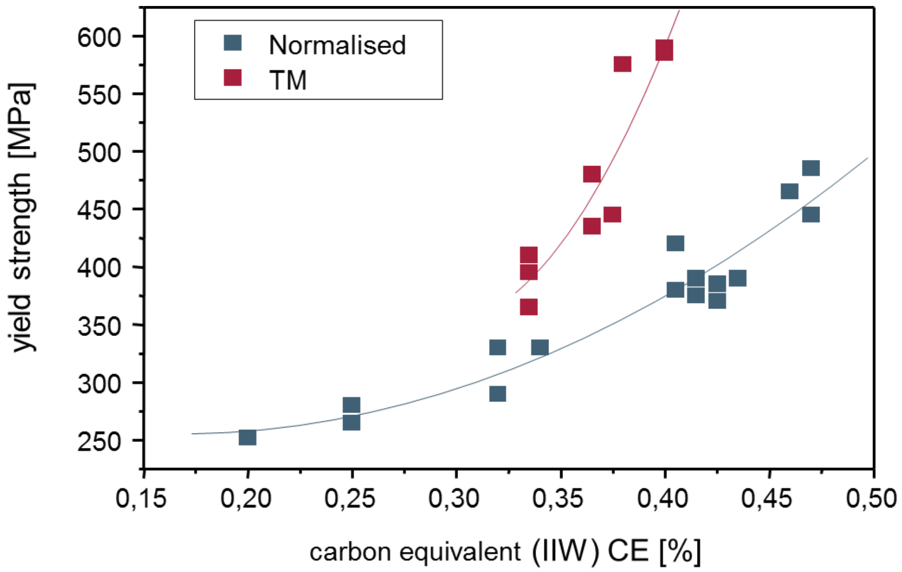

Figure 3. Yield strength as a function of alloying, expressed by the carbon equivalent CE(IIW)

Table 1. Carbon equivalent values for a typical S355J2+N and S355ML.

Steel grade	CET	CE (IIW)
S355J2+N	0.31	0.42
S355ML	0.24	0.36

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

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 [5]. 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]*).

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

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. The achievable savings on the fabrication time (no time for cooling down/heating up lead to 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 facilitates welding in constricted rooms, e.g. inside box girders.

Figure 6. record-breaking: The longest cable-stayed bridge in the world, built with 18.000 t higher strength thermomechanically rolled steel (S460ML).

Higher Strength Construction Steel

Production

Even though modern steel production methods enable steel grades with yield strength up to 1300 MPa, in classical steel construction, e.g. buildings and bridges, the usage is mostly limited to steel grades up to 690 MPa [6] (Fig. 7). 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 460 MPa
3. Quenching and Tempering: up to 690 MPa in steel construction

The latter method (process C in Fig.1) is most commonly used to obtain high strength steels and is applied subsequent to the hot rolling step (process A in Fig.1). The rolled plate is heated up until full austenitization and then rapidly cooled down by water (quenching). A very hard microstructure of martensite or bainite is formed. In order to reduce this extreme hardness and improve the toughness properties of the steel the heavy plate is afterwards tempered in a furnace. Typical high strength steel grades for constructional steelwork achieved with this heat treatment are S460Q/QL or S690Q/QL. In general theses steel grades show a good weldability when certain precautions (e.g. preheating) are taken.

Figure 7. Higher strength quenched and tempered steel (S690QL) in bridge construction. Samuel Becket Bridge in Dublin, Ireland.

Benefits on cost and sustainability

With their increased strength – while simultaneously being sufficiently weldable – these high strength steels allow notable material savings in fabrication and assembly [7]. If comparing for example the rated values for S355 and S460 (fy = 315 MPa at 100 mm plate thickness to fy = 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 component) (Fig. 4).

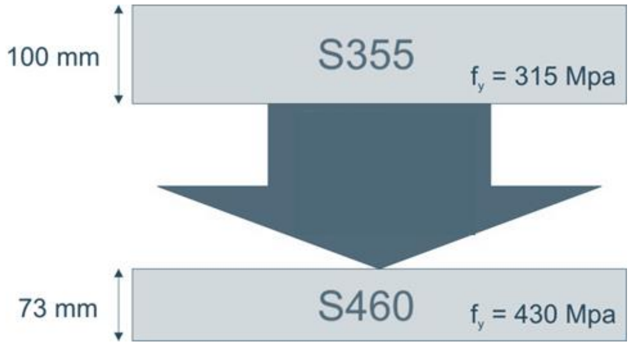

Figure 4. Possible reduction of plate thickness when using higher strength steel leads to savings in material consumption

These reduced cross sections impact the cost and eco-balance of a construction beside the reduced material amount 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 constructional steelwork.
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. 5).

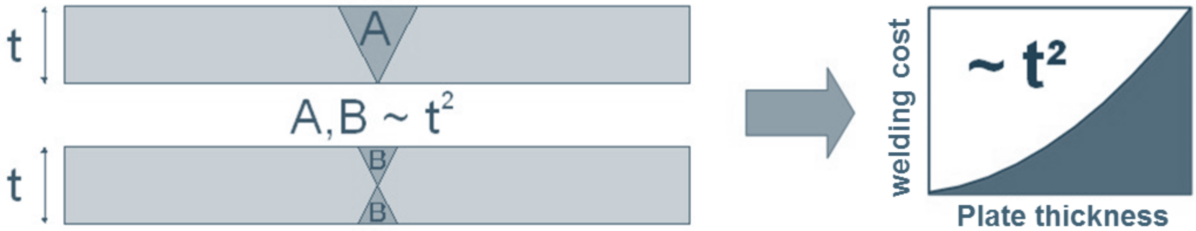

Figure 5. Realizable cost savings in welding dependent on plate thickness

A reduction of welding time as well as testing time complete the economic advantages associated with high strength steel.

Longitudinally Profiled Plates

Properties and Benefits

Another interesting product of the steel making industry is the longitudinally profiled 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 [8]. Fig. 7 gives an overview of the possible profile types.

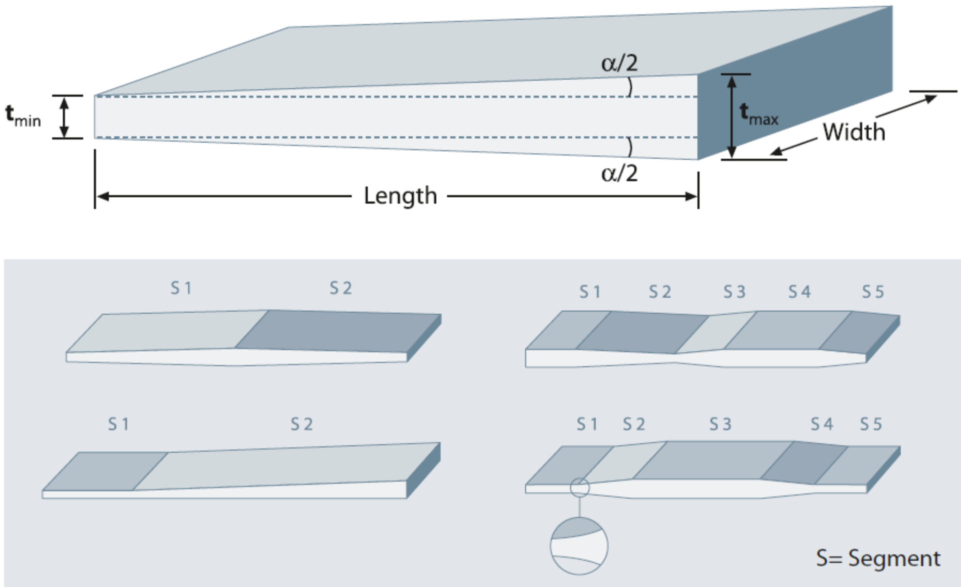

Figure 7. Overview of possible profiles for longitudinally profiled plates (LP plates)

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 statical calculations. Given that the usage of LP plates can offer a cheaper solution by representing a trade-off between redundant excess material and additional 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.

Weathering Steel

Properties and Benefits

In order to achieve weathering construction steel (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. 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 positively influence the life cycle costs of a bridge construction. However, the usage of weathering steel in bridge building has certain restriction 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 an alternation between being wet and completely dried off again.

An interesting new modern development of steel industry is a thermomechanically rolled higher strength weathering steel. It combines the benefits of lower carbon equivalent and higher strength with weathering resistance behavior. As the minimum content of alloying elements for the corrosion protection itself increases the carbon equivalents, the carbon equivalents of weathering steels are higher than the ones of normal constructional steels.

Therefore thermomechanically rolling can somewhat attenuate this disadvantage again and with that enhance the weldability of weathering steels. Such a weathering steel (ASTM A709M HPS485W) was for example successfully used in the Haliç Metro Bridge in Istanbul, Turkey (Fig. 8).

Figure 8. Higher strength weathering steel (A709M HPS485W) in bridge construction. Haliç Metro Bridge in Istanbul, Turkey

Conclusions

The steel making industry can significantly support the economic efficiency of a bridge construction by developing and refining modern steel concepts. Mainly these potential savings are associated with a reduction of energy (production energy, heating energy or transportation) or 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 steel construction.

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