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MODERN STEEL – HIGH PERFORMANCE MATERIAL FOR HIGH PERFORMANCE BRIDGES

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Abstract

Development of high performance bridges is closely linked to the availability of a new generation of steel products. Innovative production processes, which were brought into operation recently, are the key to steel grades with significantly higher properties. Particularly thermo-mechanical treatment allows to combine three essential but formerly incompatible material properties: high strength, good toughness and easy weldability.

This paper presents the production processes and explains how steel quality is affected. Information is given on chemical composition and mechanical properties: strength, ductility and toughness of different available grades. Reporting on numerous test series the paper shows the resulting benefits for fabrication processes, and especially the great improvement of weldability. It explains how modern bridge design takes advantage of available product types, dimensional ranges and steel grades. Cost optimisation and overall efficiency are discussed. Case histories are presented to illustrate the different aspects of innovations.

1 INTRODUCTION

Since the first application of steel in bridges in the 19th century the development of bridge construction has been closely linked to the developments in material properties and production methods. Significant achievements concerning strength, economy, design versatility, fabrication and erection techniques and service performance would not have been possible without the substantial improvements of steel and its many products. Particularly bridge construction, with specific high requirements for material properties, was at the origin of extensive research work which was finalized by the production of improved steel grades. Innovation in production methods during the last decade allowed the introduction to the construction market of a new generation of steel grades with high performance properties and great potential for efficient use in bridge construction.

2 PRODUCTION PROCESSES FOR MODERN STEEL PRODUCTS

The development of new steel grades was always driven by the demands of the users wishing for materials showing good mechanical characteristics such as yield strength and toughness as well as excellent fabrication properties ensuring an efficient fabrication technology in the workshop and during the erection of a steel structure. Among others there are two major ways of increasing the yield strength of steel:

- Alloying: By alloying elements such as carbon and manganese the strength of steel products can be "easily" increased. But it is known that an addition of alloying elements in most cases also worsens the fabrication properties of steel products, in particular the weldability.
- Heat treatment: Heat treatment has an effect on microstructure and grain size. The main advantage of this process consists in the achievement of a fine-grained structure resulting in

higher strength as well as better toughness of the material compared to a coarse-grained structure (relation of Hall-Petch).

For this reason the heat treatment is of major importance in the development of new steel grades. The historical context is shown in Figure 1. Until 1950 the steel which is today known as S355J2G3 was regarded as high tensile steel. As a plate this grade is usually produced by a normalizing heat treatment - a heating slightly above the A_{c3}-temperature (temperature where the ferritic-perlitic structure has totally changed to austenite) followed by a calm cooling resulting in a fine and homogeneous grain structure (see Figure 2, process B). This process can be replaced by a normalizing rolling where - simply expressed - this heat treatment is included in the rolling but leads to a similar result. By normalizing steel grades, yield strength up to 460 MPa can be reached although the alloying content may be too high to enable easy fabrication, particularly welding.

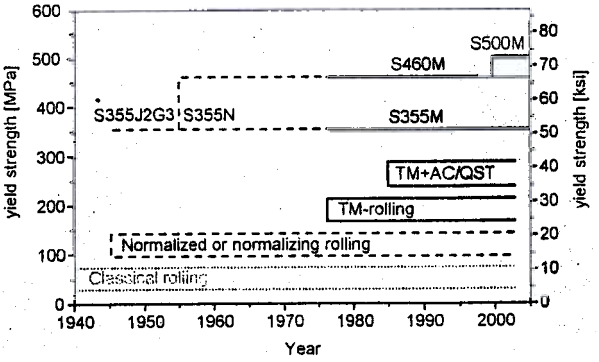

Figure 1 Historical development of production processes for rolled steel products

During the 1960-s the application of the quenching and tempering process for structural steel grades began (process C). This process consists of a rolling followed by heating above the A_{c3} temperature and a hard cooling in air or oil plus a subsequent tempering. It enables today to produce steel grades with yield strength up to 1100 MPa. However due to the higher alloying content which is necessary to get a sufficient hardening, these steel grades have up to now not found a wide application range in construction industry.

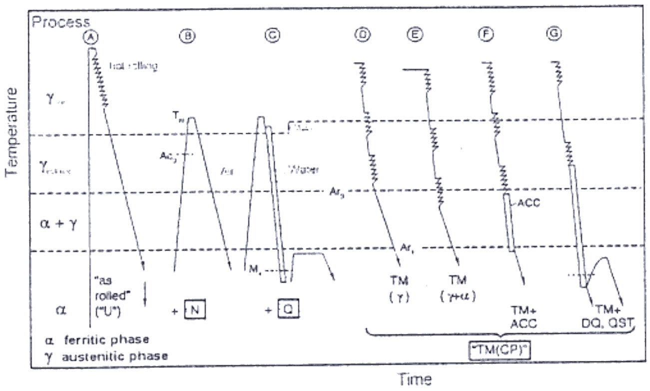

Figure 2 Different types of heat treatment processes

In the 1970-s thermomechanical rolling process was developed and first applied for linepipe plates, but then fast found the way into the fields of shipbuilding and construction of offshore platforms, both for plates and for rolled sections. TM-rolling is defined as a process in which final deformation is carried out in a certain temperature range leading to material properties which cannot be achieved by heat treatment alone. The resulting steel grade has high strength as well as high toughness and the same time a minimum alloying content as explicitly described in the following sections.

Today a large variety of different TM-processes exist. Which particular process is applied is a matter of the product shape (plate or sections), steel grade (especially yield strength) and thickness of the product.

It is usual to add to the steel some microalloying elements such as niobium, vanadium or/and titanium in a very small extent in order to achieve an additional strengthening effect by the formation of fine carbonitrides and to increase the recrystallisation temperature. First rolling passes are carried out at traditional rolling temperature. Further rolling passes are accurately defined at temperature below the recrystallisation temperature (process D) and sometimes even in the temperature range of coexisting austenite and ferrite/pearlite (process E).

For plate production this is followed by a natural cooling in air - for smaller plate thickness and lower yield strength grades - or by an accelerated cooling by water in an automatic accelerated cooling line (process F). For very thick plates and higher yield strength grades a tempering process generally follows accelerated cooling.

For beams quenching and self-tempering is used (process G). In this process an intense water-cooling is applied to the entire surface of the beam after the last rolling pass. Cooling is stopped before the core is affected. Thus the outer layers of the beam are tempered by the flow of heat flux from the hotter core to the colder surface region (Figure 3).

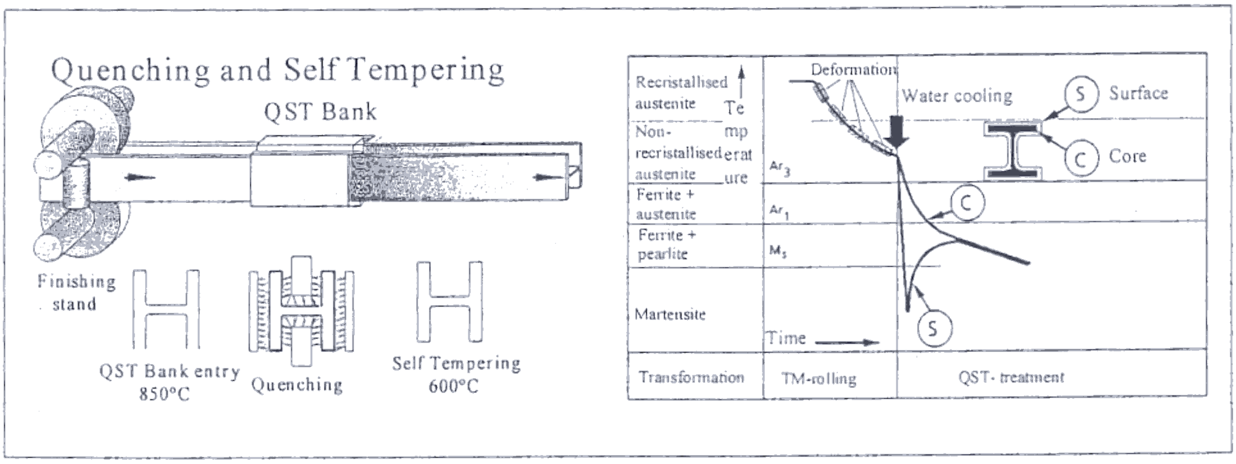

Figure 3 Schematic illustration of the QST-process

All these varieties of the TM-process produce a very fine-grained microstructure as shown in Figure 4, avoiding high alloying content and therefore providing very good toughness properties and an excellent weldability. Furthermore high yield strength grades can be produced by these techniques. Plates with guaranteed minimum yield strength value up to 500 MPa are available in thickness up to 80 mm and are already used in shipbuilding and offshore construction.

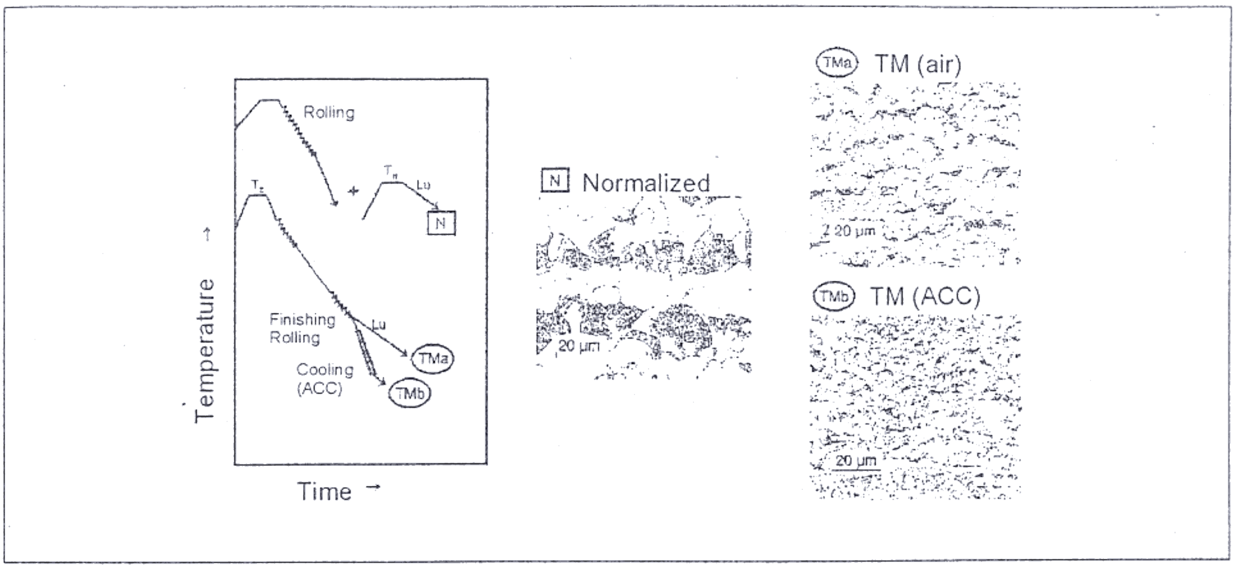

Figure 4 Grain microstructure of TM-steel compared to normalized steel (S355ML)

3 PROPERTIES OF TM-STEEL

Thermomecanically rolled steel products for usage in bridge structures are currently standardised in the European standard EN 10 113-3 [1] which defines four different yield strength levels: S275, S355, S420 and S460. For each yield strength level there are two grades: grade M with toughness values tested by Charpy-V notch impact test at -20°C and the low-temperature ductile grade ML with toughness tested at -50°C. Table 1 gives the guaranteed mechanical values of the three yield strength levels S355, S420 and S460 as defined in the standard.

Table 1 Mechanical properties of TM-Steel grades according to the standard EN 10113-3

	Tensile strength R_m [MPa]	Yield strength R_{eH} [MPa]			Elongation A_5 [%]	Charpy - V Impact test	
		≤ 16 mm	> 16 mm ≤ 40 mm	> 40 mm ≤ 150 mm		Temperature [°C]	Absorbed Energy [J]
S355M	450- 610	355	345	335	22	-20	40
S355ML						-50	27
S420M	500 - 660	420	400	390	19	-20	40
S420ML						-50	27
S460M	530 - 720	460	440	430	17	-20	40
S460ML						-50	27

63 mm is maximum thickness for flat products

Although EN 10 113-3 defines plate products only up to a thickness of 63 mm, heavy plates made of TM-steel are today available in a thickness of up to 120 mm according to different mill standards. Therefore in the coming revision of the above standard, the prEN 10 025-4, TM-steel plates will be included with thickness up to 120 mm.

For sections the TM-QST process is currently applicable to the shapes IPE ≥ 500, HE 260 - HE 1000/ HL 1100, HD 260-400 and the corresponding sizes of the British BS 4 and American ASTM A6 standardized section series. Flange thicknesses range up to 125 mm.

It has to be emphasized that the property values given by the standards are minimum values and that actual production values exceed by far the minimum requirements. As an example Figure 5 displays for comparison the transition curves of the Charpy-V absorbed impact energy against test temperature for TM-steel S355ML and conventional steel S355J2G3. It can be seen that,

the TM-steel shows a significantly higher toughness value at room temperature, exceeding even 300J. the transition from ductile to brittle fracture behaviour, as well as the temperature at which 27 J is reached, are shifted to much lower temperature in comparison to S355J2G3.

By this excellent ductile behaviour a highest extent in structural safety is guaranteed and an easy fabrication process, for instance welding or cold bending, is enabled.

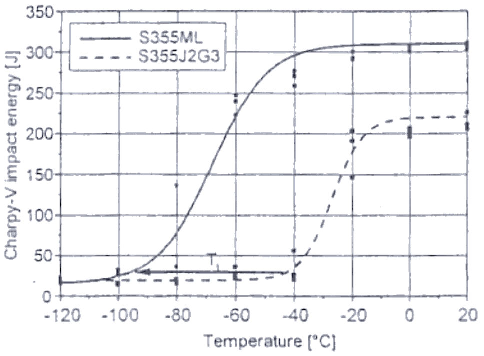

Figure 5 Charpy-V transition curves of TM-steel S355ML and conventional S355J2G3 grade (plate, 60 mm thickness)

As far as the yield strength of TM-steel is concerned, EN 10113-3 specifies a decrease of the guaranteed yield stress for increasing thickness. But the production process allows, if specified, to guarantee the nominal values of 355, 420 or 460 MPa for the full range of product thicknesses. Hence this order option allows further design optimisation.

Table 2 Chemical composition of S355J2G3 and TM-grade S355ML

	S355 J2G3		S355 ML	
	EN 10025 (%)	typ. analysis (%)	EN 10113-3 (%)	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	1,45
P	< 0,035	0,018	< 0,030	0,012
S	< 0,035	0,015	< 0,025	0,005
Nb	-	-	< 0,05	0,02
V	-	-	< 0,10	-
Mo	-	-	< 0,20	-
Ni	-	-	< 0,30	-
CE		0,42		0,32
Pcm		0,26		0,16
CET		0,32		0,23

carbon equivalent values:
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

Table 2 compares the chemical composition of TM-steel S355ML and conventional S355J2G3 grade. Both the maximum content according to the standard requirements and the typical plate production values are listed. It can be seen that by the use of the TM-process the carbon content can be significantly reduced. Consequently the carbon equivalent values are much lower, enabling an easy and efficient welding process without danger of cold cracking. Even for S460M steel the CE-value does normally not exceed that of a typical S355J2G3 grade, so that welding is not more difficult than for conventional steel.

Some applications, for instance according to prEN 1993-1-10 [2], demand for improved deformation properties in through-thickness direction. For these cases TM-steel can be produced to meet the ductility criteria defined in EN 10164 [3] for Z classes with a minimum of 15, 25 or 35% reduction of area.

Today, most national design codes include TM-steel grades for applications in bridge construction (German DIN 18800-1 in conjunction with the Anpassungsrichtlinie Stahlbau, French CCTG Fascicule 4 Titre III,...). The coming Eurocode 3-2 will cover all TM-steel grades of the material standard EN 10113-3 (yield strength up to 460 MPa; thickness range up to 150 mm).

4 FABRICATION PROPERTIES OF TM-STEEL

In addition to producing steel grades with superior material properties, thermomechanical rolling processes were developed to enable cost savings during fabrication at workshop and on site. Especially optimised welding process was aimed at.

Figure 6 shows the calculated preheating temperature for an S355ML grade - depending on the hydrogen content of the welding consumable - for two different heat input levels. Calculations are in accordance with EN 1011-2, annex C method B [4]. It is understood that preheating can be completely avoided under suitable conditions for this steel grade due to the very low carbon equivalent value. Thus, considerable advantages are offered in comparison to the ordinary S355J2G3 which has to be preheated to a temperature of 130 - 150 °C under the same welding conditions.

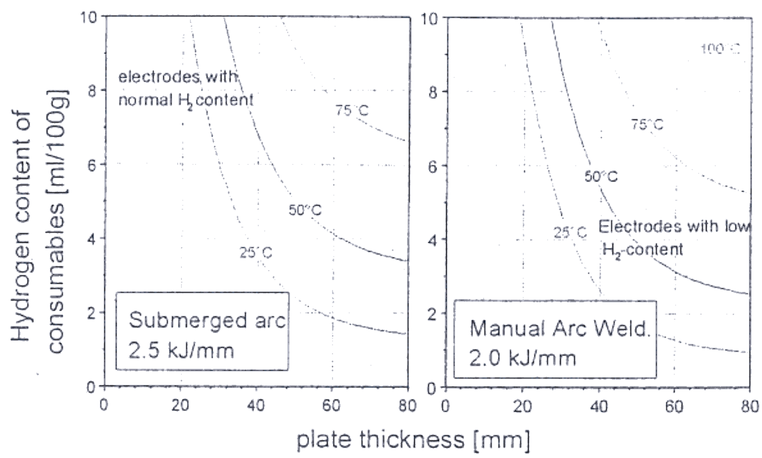

Figure 6 Preheating temperatures for welding of S355ML

Even the high-strength grade S460ML is not difficult to weld. Usually the preheating temperature is not higher than for conventional S355J2G3. Many case studies have shown that S460ML can often be welded without preheating, even with thickness up to 80 mm.

TM-steels are not only characterised by advantageous opportunities in choosing the welding procedure but also provide outstanding properties after welding. A comparison of weldability of TM-steels and normalized steels is given in Figure 7. Calculation of hardness values in the heat affected zone for an extended range of heat input level shows values below 350 HV for TM-grades and no risk of cold cracking.

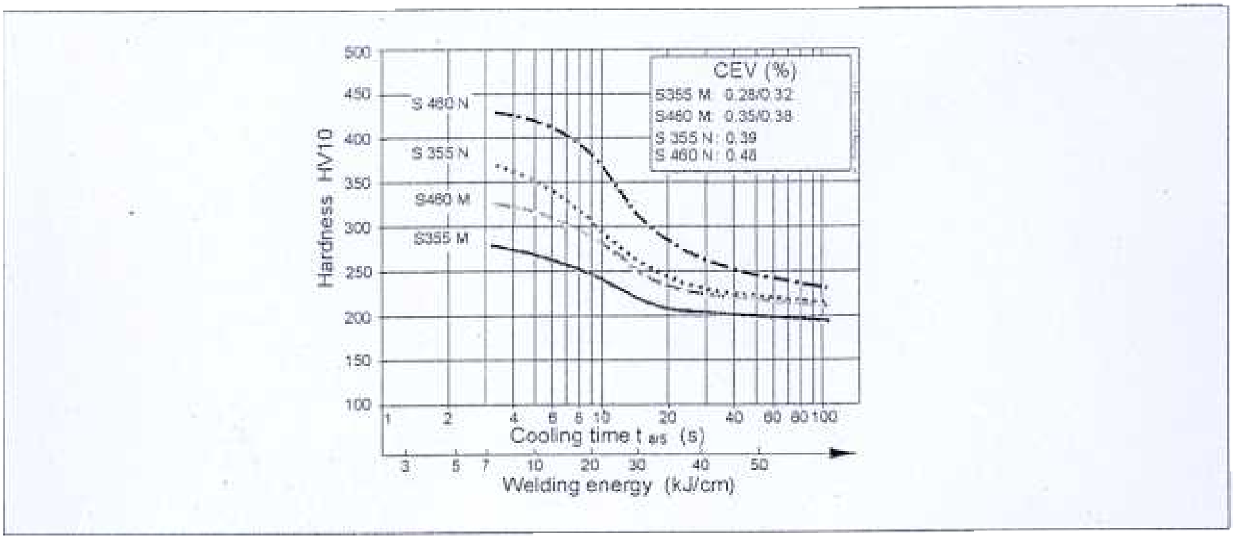

Figure 7 Hardness curves after welding

Comprehensive tests were carried out with different grades and welding parameters to verify the properties after welding [5]. Tensile properties are maintained. Figure 8 shows test results for S355 ML and S460 ML.

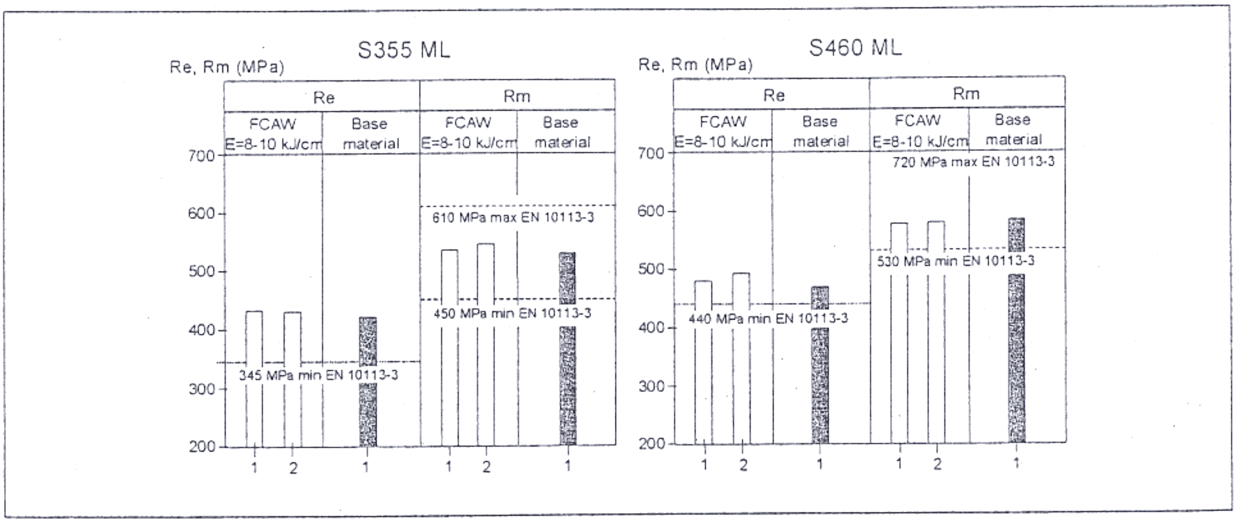

Figure 8 Tensile properties after welding of S355 ML and S460 ML (full penetration butt weld, flange thickness = 40 mm)

Examples of measured HV 10 hardness at several locations within filler metal, heat affected zone (HAZ) and base metal are given by Figure 9. Neither appreciable hardening nor softening effects could be observed.

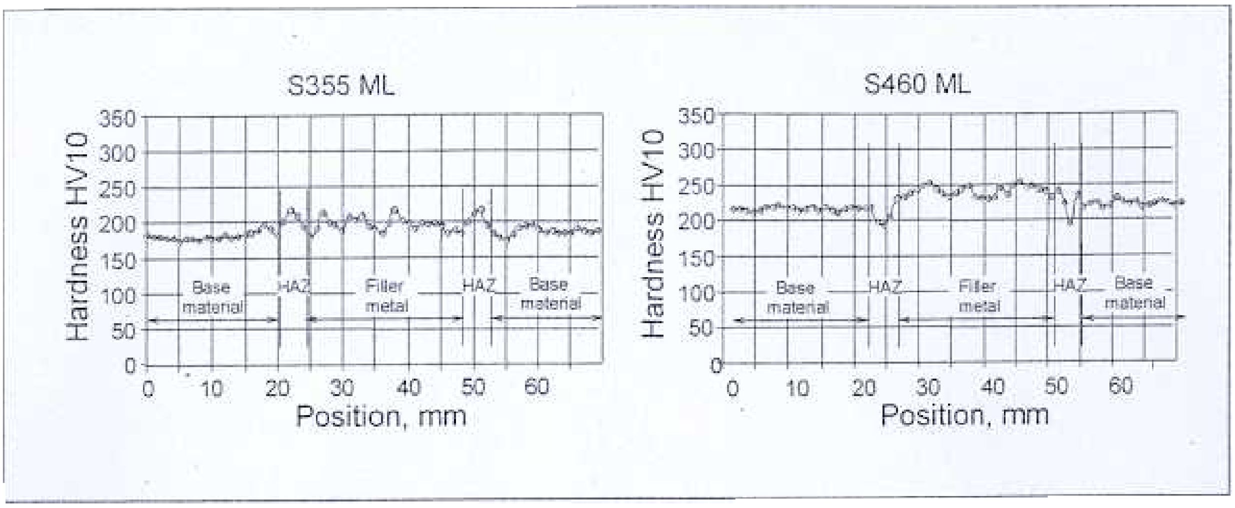

Figure 9 Hardness measurements after welding (full penetration butt weld, flange thickness = 40 mm)

Figure 10 displays the Charpy-V impact energy values measured after welding at various locations of the HAZ for different welding energy levels. Obviously excellent toughness values are guaranteed, mostly in excess of 100 J. Good ductility values can also be achieved if a high-heat input welding process is applied. Thus, higher welding energies can be used without affecting structural safety of the structure.

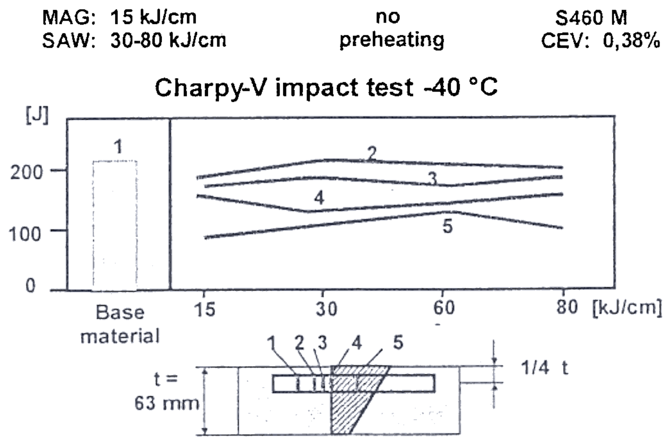

Figure 10 Toughness measured in weld material and heat affected zone of S460M rolled beam

Flange cutting has similar effects on the material than welding. Low CE content of TM-steels eases the process, avoiding excessive local hardening at cutting edge and subsequent risk of surface cracking. Preheating is generally not required, except for very thick material.

Some restrictions on the use of TM-steel are required if hot forming is concerned. High material temperature (>580°C) maintained during extended period leads to a change of the grain structure and the material properties which cannot be recovered upon cooling to low temperatures, because they are produced specifically during the original rolling process. Consequently, TM-steels should not be used for applications requiring hot forming, unless strength and toughness modifications are taken into account.

Flame straightening is not subject to the same restrictions. This process consists in localized rapid heat input with thermomechanical-type influence on microstructure. Numerous tests have been performed, resulting in detailed procedures for different types of straightening [6]. They can be summerized as follows: Flame straightening with heating lines, which heat the surface-near part of the structure, is possible up to a material temperature of 900-950°C, without observing a drop either in strength or in ductility. When straightening by heat points or wedges, a maximum temperature of 700°C should be obeyed, because the holding time at high temperatures is significantly extended.

12 NEW STEEL GRADES AND BRIDGE CONSTRUCTION

Typically bridge structures carry heavy, dynamic and cyclic loads over long spans and during a long life. Safety and durability criteria are resulting in stringent requirements for material quality. Therefore the achievements in material properties enabled by the newly developed production processes generate substantial benefits for bridge construction.

Compared to classical grades, thermomechanical steel grades offer greatly increased toughness. Combined to excellent ductility this means a higher material strength for impact and seismic loading. The influence on overall safety of bridge structures is accordingly beneficial.

The level of toughness required to avoid brittle fracture depends on numerous factors such as service temperature, strength grade, stress level, strain rate, construction detail and material thickness. Recently carried out investigations, which are based on fracture mechanics, have ended up in practical tools for the selection of the grade which fits the particular design condition [7]. Figure 11 (based on ENV 1993-2 :1997) shows the limiting thickness for typical bridge parts in tension depending on yield strength, for a lowest service temperature of –30°C and provided that the appropriate toughness level is guaranteed.

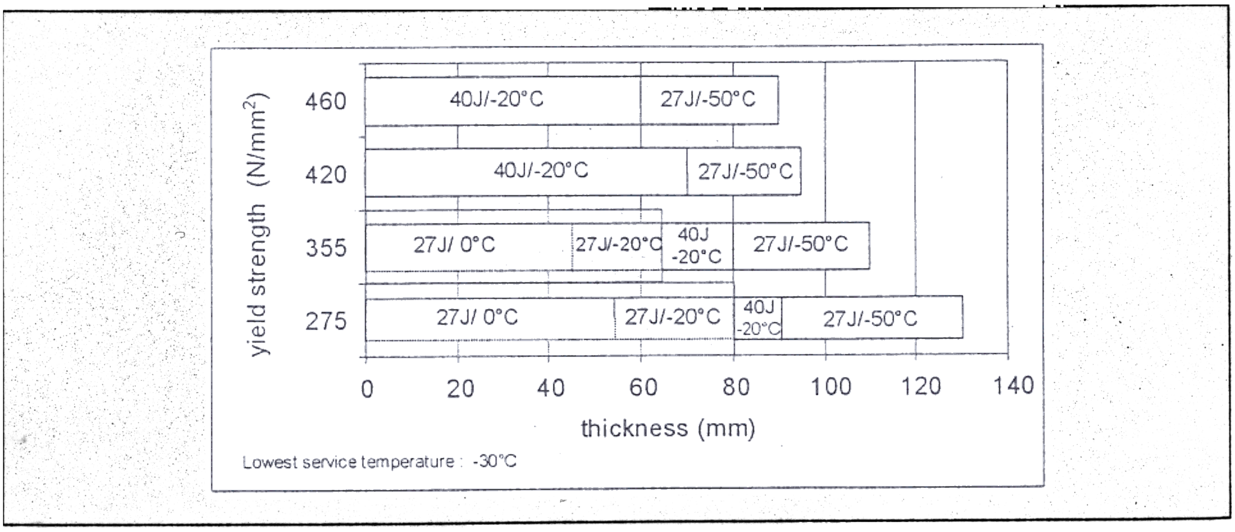

Figure 11 Thickness range for typical bridge parts in tension in accordance with ENV 1993-2:1997

The shaded area corresponds to the thickness range which is covered by steel grades produced by classical production process. The huge step achieved through increased toughness of the new grades is obvious: much thicker products may be safely used for bridge structures.

The new material availability influences the design of structural elements. In former times, for heavily stressed parts such as flanges at mid-span and over interior supports, additional plates were added in order to build-up the required cross section area. The involved welding or bolting operations and complicated splicing details are costly fabrication items. With thicker single parts these fabrication steps can be avoided. On the other hand it is well known that fatigue strength depends essentially on constructional detailing. As-rolled sections and plates are less prone to damage than welded details. Eliminating additional reinforcing parts improves the fatigue strength.

Weldability is one of the major criteria to be considered if rating the performance of steel grades. In this respect TM-steel grades definitely have outstanding properties if compared to classical grades. The method for producing fine grained steel by in-line heat treatment and not by adding alloying elements proves to be the best choice. In addition to cost efficiency in production it leads to chemical composition with substantially lower CE values and consequently much better weldability :

For most situations preheating is not needed, even with great material thickness. Case studies have shown resulting cost savings of 25 to 60€/ton.

Base material allows heat input during welding ranging typically from 8 to 60 kJ/cm. Thus a variety of different welding processes can be applied, allowing to choose for every situation the most time- and cost efficient process, both for workshop and on site welding.

Tolerance towards deviation of welding parameters is high. Risk of imperfections and need for repair is consequently minimised.

The new processes enable the production of high strength grades, i.e. with a yield strength of 420 and 460 N/mm^2 (Figure 4.1), exceeding the 355 N/mm^2 of the currently most common grade used in bridge construction. These grades fully meet the toughness and ductility requirements, are easily weldable and are produced with small extra cost compared to lower strength grades. The common availability allows thus the wider use for bridge applications.

As a result of designing structural elements in high strength steel, size of cross section and especially material thickness are reduced. Consequently steel weight is lower and material cost saving is achieved. Figure 12 shows the steel girder specification of comparative design in different steel grades for a typical small span composite bridge. The weight reduction if using S460 instead of S355 is as high as 25% and the material cost saving is 21%.

Steel grade	S235	S355	S460	S460
Section	HE 1000 M	HE 700 M	HE 800 A	HE 700 B
Construction depth (m)	1,38	1,09	1,17	1,08
Steel weight	+16%	reference	-25%	-20%
Material cost (beams)	+7%	reference	-21%	-17%

Figure 12 Comparative design of 17m-span road bridge

Beyond material cost advantage, weight reduction eases transport and erection. Lower permanent loads need lower foundation bearing capacity. This fact is essential in the case of reconstruction of a bridge deck on existing piers and abutments. Dead weight of movable bridges governs design of mechanical parts and high strength steel allows cost saving which exceed by far the material cost advantage.

Reduced material thickness is a great advantage in case of welded splices. Especially for highly stressed parts, weld volume reduction of butt splices is spectacular: 40 to 60% (V and double V full penetration).

For some applications the question arises whether the use of high strength steel >S355 is justified:

To prevent parts under compression from buckling (local, flexural, lateral torsional buckling), minimum dimensions or thickness are required. Depending on slenderness of the element, stiffness criteria may govern design, as resistance may not be increased by higher yield strength.

Limitation of deflection under traffic loads or deck vibration control for comfort and safety purposes may influence design to such an extent that stiffness rather than load capacity becomes the major criterion and that no advantage can be taken from a higher yield strength of steel. Highway bridges are generally not critical in this respect, but railway bridges (particularly for high-speed traffic) and lightweight footbridges are typical categories with such conditions. The choice of stiff structural systems such as composite girders and trusses helps to avoid such situations.

Figure 13 illustrates the influence of stiffness criteria on steel grade selection for typical single span railway bridges (composite filler beam decks). Cost optimized design is performed for a span length ranging from 5 to 35 m [8]. Limiting values for maximum vertical deflection for passenger comfort at train speed of 160 km/h are in accordance with ENV 1991-3. For a span length below 25 m deflection or vibration govern design and optimum steel grade of beams is S275 or S355. For longer spans permanent loads predominate over traffic loads and high strength grades are the best choice for overall economy.

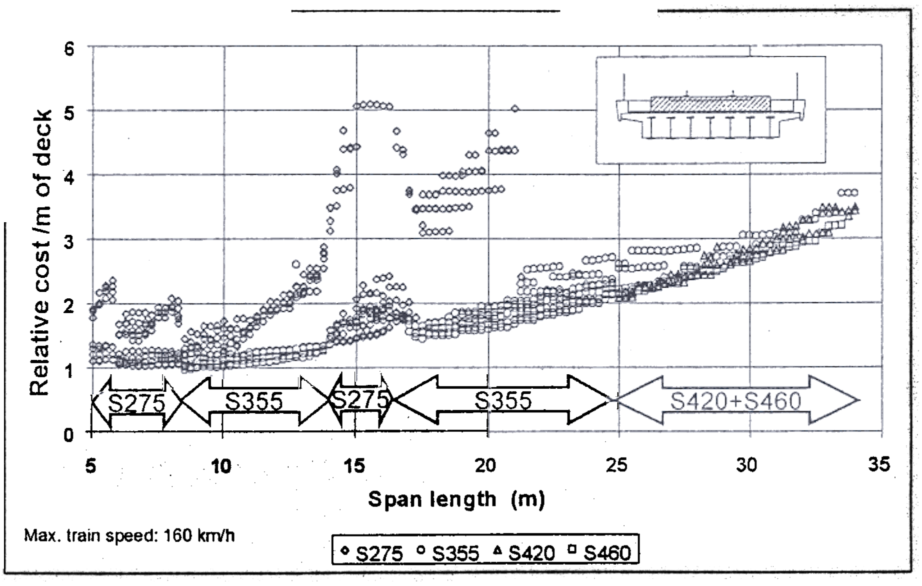

Figure 13 Steel grade selection for optimized design of single span railway bridge (composite filler beam deck)

Fatigue strength of assembling details is independent of yield strength. Safe design is achieved by limiting stress range to a reference value, which depends on detail category. Good detailing is therefore essential, otherwise no advantage can be taken of higher tensile properties. When permanent loads predominate, fatigue is less critical and S420 and S460 should be generally considered.

During the last decade the new TM-type steel grades have been successfully used for the construction of a number of bridges throughout the world. Some of them are well known outstanding realizations such as the Normandy Bridge in France, the Erasmus Bridge in Rotterdam and the Øresund Crossing as part of the link between Sweden and Denmark, other examples are smaller projects. The bridges were designed in grade S355 M and, for those parts where high strength grade is appropriate, in grade S460M.

For some projects comparative predesigns were carried out for both S355 and S460 solutions, before taking decision on final design: Mjösund bridge, Norway (composite steel box girder-concrete slab); A16 Motorway overbridges, France (composite twin rolled beams–concrete slab); Erasmus bridge, Netherlands (cable stayed orthotropic deck). Weight reduction of 18-30% and cost saving of 10-12% showed superiority of high strength steel over S355.

6 CONCLUSIONS

Advanced thermomechanical rolling processes are the key to a new generation of fine-grained steel grades with high strength, good toughness and excellent weldability, a combination of material properties which cannot be achieved by traditional production techniques. The product range includes plates and sections with great material thickness and yield strength up to 460 MPa. In-depth investigation of fabrication properties and comprehensive testing show the superiority of TM-steels, particularly for welding. The use of the new grades in bridge construction generates substantial benefits in the fields of safety, efficiency and cost reduction. Common availability of S460 high strength steel, with similar fabrication properties than lower grades, opens new opportunities for further weight and cost optimization as demonstrated by several case histories.

7 REFERENCES

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