Winning performance

High strength steel can now meet weldability demands as well as structural requirements, report *Marc Hever* and *Falko Schröter*

Since bridges first made use of steel in the 19th century, their development has been closely linked to developments in the material's properties and production methods. In particular, the requirements of the industry were one of the factors that drove research work to develop better steel grades through the improvement of the production process.

The development of new steel has always been driven by the demands of users, looking for good mechanical characteristics such as yield strength and toughness as well as excellent fabrication properties. Two main ways of increasing the yield strength of steel are by alloying or by heat treatment. The former involves alloying elements such as carbon and manganese to increase the strength of steel products but in most cases, this is at the cost of its fabrication properties, in particular, weldability. By using a suitable heat treatment, microstructure and grain size of the steel can be optimised in such a way that a fine-grained structure is obtained, resulting in higher strength and at the same time, better toughness.

Until 1950, that steel which is now known as S355J2G3 was regarded as high tensile steel. As a plate this grade is usually produced by a normalising heat treatment, resulting in a fine and homogeneous grain structure. The alternative is a rolling process, known as normalising rolling, leading to similar material properties. Normalised steel grades may attain a yield strength of up to 460MPa, but the alloy content may be too high to enable easy fabrication, particularly welding.

The quenching and tempering process was introduced in the 1960s; the steel is rolled, then heated above the A_{c3} temperature and cooled rapidly in air or oil plus a subsequent tempering. By this process, steel grades with a yield strength of up to 1100MPa can be produced today, although because of the higher alloy content which is necessary to get this hardening, these steel grades are not widely used in the construction industry.

Thermomechanical rolling was developed in the 1970s and initially applied to pipeline plates, but fast found its way into shipbuilding and construction of offshore platforms, both for plates and for rolled sections. TM rolling is defined as a process in which the 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 toughness and at the same time, a minimum alloy content.

Today, a large range of TM processes exist and it is usual to add a small amount of a microalloying element such as niobium, vanadium or/and titanium in order to achieve the additional strength created by the formation of fine carbonitrides and to increase the recrystallisation temperature. Initial rolling passes are carried out at the traditional rolling temperature, while further rolling passes are accurately defined at a temperature below the recrystallisation temperature, or sometimes even in the temperature range of coexisting austenite and ferrite/pearlite.

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 in water on an automatic accelerated cooling line. For very thick plates and higher yield strength grades a tempering process generally follows accelerated cooling.

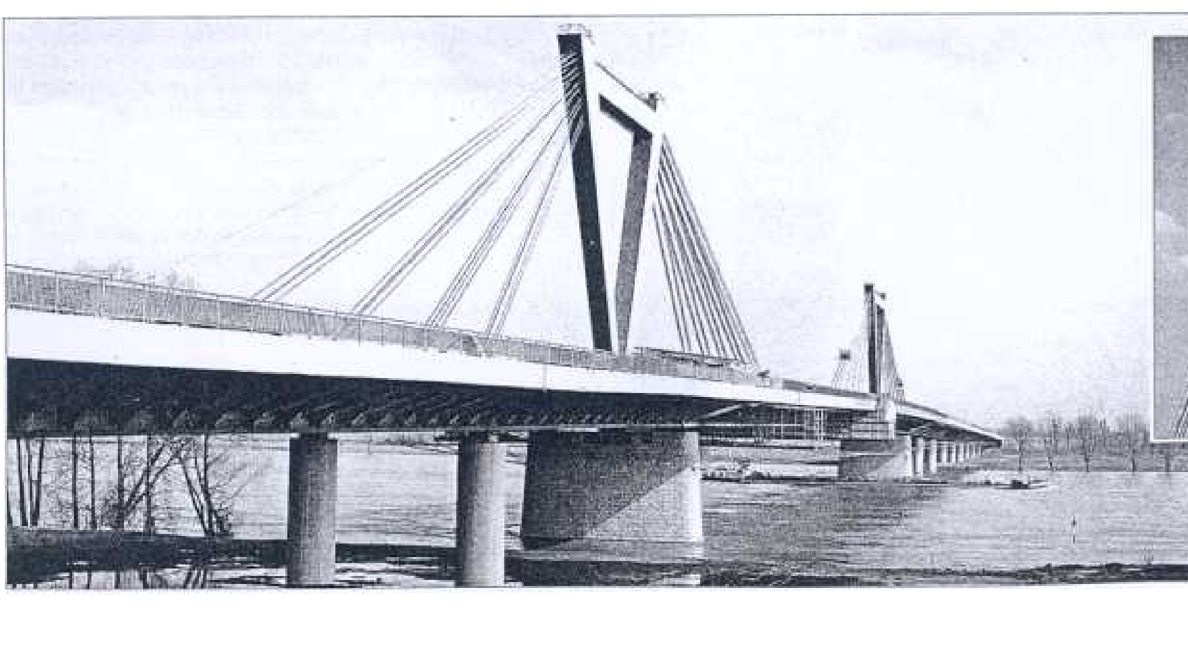
Quenching and self-tempering is used for the production of beams. In this process, intense water-cooling is applied to the entire surface of the beam after the final rolling pass but cooling is stopped before the core is affected. Thus the outer layers of the beam are tempered by the flow of heat flux from the hotter core to the colder surface region.

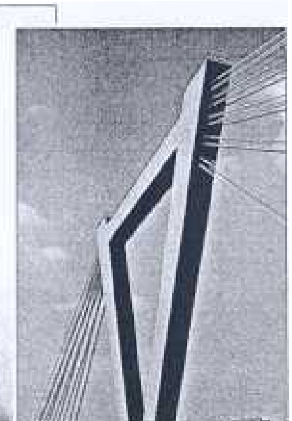
These processes create a very fine-grained microstructure, avoiding high alloy content and therefore providing good toughness properties and an excellent weldability. Furthermore, high yield strength grades can be produced by these techniques. Plates with a guaranteed minimum yield strength value of up to 500MPa are available in thicknesses of up to 80mm, and are already being used in shipbuilding and offshore construction.

Thermomechanically-rolled steel products for use in bridge structures are currently standardised in the European standard EN 10 113-3 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.

But EN 10 113-3 defines plate products up to only 63mm thick, whereas heavy plates made of TM steel are now available up to 120mm thick, depending on different mill standards. Therefore in the planned revision of the above standard, prEN 10 025-4, TM steel will be included with thicknesses of up to 120mm for plates and 150mm for long products.

It is important to point out that the properties given by the standards are minimum values and that actual production values far exceed the minimum





Ilverich Bridge in Germany, where S460ML has been used in the upper part of the pylons requirements. For example in a comparison between tests of TM steel S355ML and conventional steel S355J2G3, the TM steel shows a significantly higher toughness value at room temperature, exceeding even 300J. Meanwhile, the transition from ductile to brittle fracture behaviour, as well as the temperature at which 27J is reached takes place at a much lower temperature in TM steel.

This impressive ductility is a key to guaranteeing structural safety and enabling an easy fabrication process, for instance in welding or cold bending.

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 if required, the production process can guarantee the nominal values of 355, 420 or 460MPa for the full range of product thicknesses, offering further design optimisation.

A comparison of the chemical composition of TM steel S355ML and conventional S355J2G3 grade also shows that use of the TM process can significantly reduce the carbon content.

Most national design codes today include TM steel grades for applications in bridge construction, and the coming Eurocode 3-2 will cover all TM steel grades of the material standard EN 10113-3.

Compared to traditional grades, thermo-mechanical steel grades offer greatly improved toughness. Combined with excellent ductility this means a higher material strength for impact and seismic loading. Recent investigations based on fracture mechanics have resulted in practical tools for the selection of the grade which fits the particular design condition. Increased toughness in the new grades enables much thicker products to 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. 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 compared to standard grades; in-line heat treatment proves to be the best method of creating fine-grained steel. As well as cost efficiency in production, it leads to a chemical composition with substantially lower carbon-equivalent values and consequently much better weldability.

For most situations, preheating is not needed, even when the material is very thick. Case studies have shown resulting cost savings of 25 to 60 €/ton. Another advantage is that the base material allows heat input during welding ranging typically from 8 to 60kJ/cm. Thus a variety of different welding processes can be applied, allowing the welder to choose the most time and cost efficient process every time. Tolerance towards deviation of welding parameters is high, meaning that the risk of imperfections and need for repair is minimised.

Flame cutting has similar effects on the material as welding. The low carbon-equivalent content of TM steels eases the process, avoiding excessive local hardening at the cutting edge and the subsequent risk of surface cracking. Preheating is generally not required, except for very thick material. However, 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 involves the use of localised rapid heat input which has a thermomechanical-type influence on the microstructure. Flame straightening with heating lines, which heat the surface 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.

By designing structural elements in high strength steel, the size of cross section and material thickness in particular can be reduced. Consequently the steel weight is lower and cost savings in material can be achieved. For a typical small span composite bridge, the use of S460 instead of S355 for the bridge girders can bring about a weight reduction of up to 25% and a material cost saving of 21%.

Weight reduction does not translate only to material cost savings - additional savings can be made on transport and erection. Lower dead loads require a lower foundation bearing capacity, a factor that is particularly important when a bridge deck is being rebuilt on existing piers and abutments. The dead weight of movable bridges governs the design of mechanical parts and high strength steel allows cost savings which far exceed the material cost advantage.

Top: Prince Claus Bridge in Utrecht, opened last year, has a superstructure of high grade steel

Right: A19 motorway overbridge in Bentwisch, Germany. Main girders are rolled beams in TM grade S460M

Reduced material thickness has great advantages in terms of welded splices; for highly-stressed parts in particular, the weld volume of butt splices can be reduced by between 40% and 60% on V and double V full penetration welds.

However, there are some instances where the use of high strength steel may not be appropriate. For example, minimum dimensions or thickness are required to prevent elements under compression from buckling; depending on the slenderness of the element, stiffness criteria may govern design, as resistance may not be increased by higher yield strength.

Another case is where the 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 gained 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.

During the last decade the new TM steel grades have been used for the construction of a number of bridges throughout the world. Some of them are well-known crossings such as the Normandy Bridge in France, the Erasmus Bridge in Rotterdam and the Øresund Crossing between Sweden and Denmark, but there are other, smaller examples. The bridges were designed in grade S355M and, for those parts where higher strength was appropriate, in grade S460M.

For some projects comparative designs were carried out for both S355 and S460 solutions, before a decision was taken on the final design. Structures such as the Mjösund bridge in Norway, which is a composite steel box girder with concrete slab; the A16 motorway overbridges in France, composite twin rolled beams with concrete slab, and the Erasmus bridge, Netherlands, a cable-stayed orthotropic deck. Weight reductions of between 18% and 30% and cost savings of up to 12% demonstrated the advantages ■

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