Modern high strength Nb-bearing structural steels

In today's environmentally conscious and economically sensitive markets the construction sector is using ever greater tonnages of higher strength steels. This not only affords for audacious projects but also permits significant savings to be made, enabling an earlier return on investment. However, apart from the standard mechanical properties, such steels have to meet increasing performance requirements, taking into consideration on-site weldability, cold temperature performance and other environmental conditions such as seismic zones.

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Traditionally, higher strength steels have been achieved by increasing the amounts of alloying elements. However, this results in higher hardenability and may lead to an increased risk of brittle fracture and hydrogen induced cracking during welding if the correct parameters are not applied. Today, modern mills are capable of producing steel plates with yield strengths of 500MPa at thicknesses approaching 100mm. These steels are classed as fine-grained weldable microlloyed steels. They exhibit excellent toughness both within the base metal and the heat-affected zone (HAZ) of the welded joint. Typically these steels are made via the thermo-mechanically controlled processed (TMCP) route coupled with accelerated cooling and generally do not require any pre-heating prior to welding. The standard (EN 10025-4) covers TMCP steel grades with minimum specified yield strengths of 275, 355, 420 and 460MPa and specified minimum impact toughness down to -20°C (designated M) or -50°C (designated ML).

TMCP

Figure 1 illustrates the general evolution of structural steels. In particular it highlights the different processing routes from TMCP (moderate yield strengths and higher toughness) through to steels produced via the quenched and tempered (Q+T) route for the very high yield strengths (1,100MPa). For TMCP steels, excellent properties can be achieved by a leaner alloying content coupled with small amounts of microalloying with niobium (Nb).

The principles of Nb microalloying and its beneficial effects as a grain refiner (higher strengths and improved toughness) and permitting reduction of carbon and other alloys are well established. *Figure 2***[1]** highlights the advantage of reduced carbon equivalent (CEq) for a given strength of TM-rolled steel in comparison to traditional normalised routes. Nevertheless, it is important to note that, dependant on the required strength and toughness, for a given plate thickness, the correct processing schedule

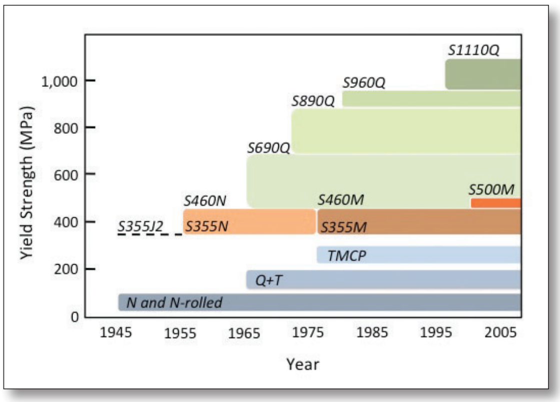

Fig 1 **General evolution of structural steel**

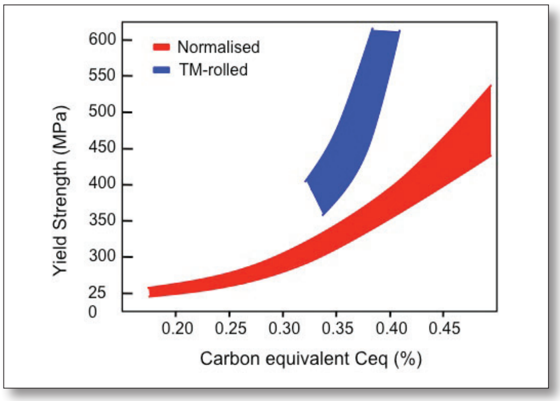

Fig 2 **Relationship between yield strength and carbon equivalent**

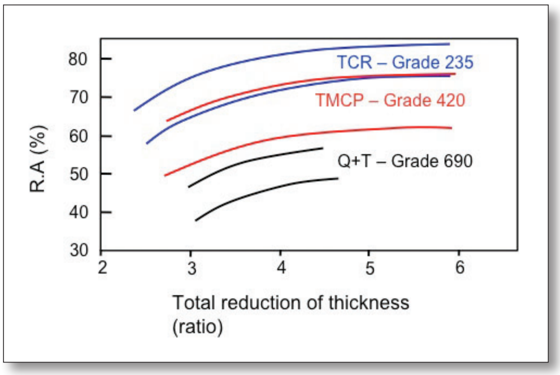

Fig 3 Influence of per pass reduction on properties

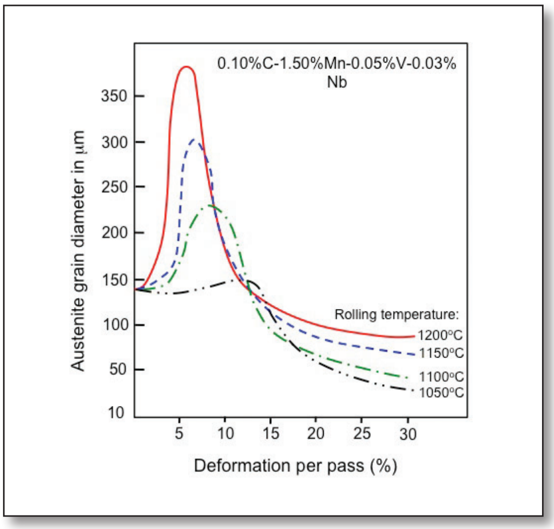

Fig 4 Recrystallised austenite grain size in pre-rolling of microalloyed steels

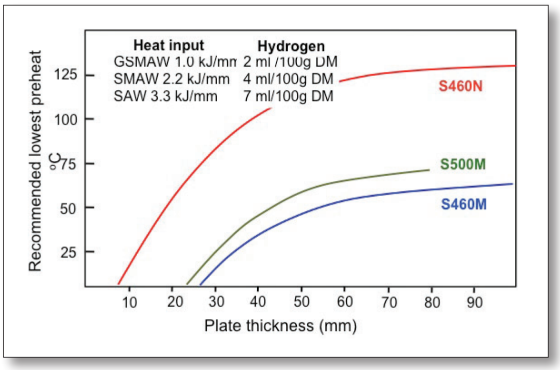

Fig 5 Calculated preheat temperatures as a function of plate thickness – moderate restraint

must be applied giving consideration to the steel chemical composition. For example, when rolling thick plates it is important that the maximum possible reduction is given per pass, in particular during the earlier stages. This helps to ensure that the slab is deformed through to the core, resulting in good toughness properties (see *Figure 3***[2]**). In addition, when rolling microalloyed steels, it is also important to note that in the recrystallisation temperature range, sufficient deformation per pass is given to prevent grain growth occurring at lighter passes (ie, <10%) as illustrated in *Figure 4*. Both of these factors are important for structural plates subjected to through-thickness loading, and both EN 1993-1-10 and EN 10164 are normally specified for through-thickness ductility properties.

Studies have shown that first, the steel must not be brittle at the intended working temperature and second, it should exhibit sufficient ductility to withstand any crack propagation. The trend in crack tip opening displacement (CTOD) test requirements for offshore plates demonstrates the increasing performance requirements of modern structural plate in which recent projects (eg, at Sahkalin) have required testing at -40°C and Charpy toughness CVN requirements down to -60°C for steels with 460MPa yield strength. Fracture mechanics tests show that larger flaws and higher strength steels require for higher toughness in order to have a safer construction. The challenge for steel metallurgists is therefore to develop steels that possess both higher strengths (ie, above 450MPa) as well as better toughness. This can be achieved through a better understanding of the alloying and entire process route. Typically this will involve:

- Reducing the volume fraction of the pearlite by using lower carbon content. A low carbon and highly clean steel also has a positive effect on weldability.
- Vacuum degassing during secondary metallurgy to minimise sulphur, nitrogen, hydrogen and the total oxygen content. Overall, this will result in reduced tramp elements and a cleaner steel.
- Ca treatment to modify any sulphide inclusions making them more globular. Today the typical sulphur content in an aluminium deoxidised steel has <0.003 %S.
- Soft reduction to shrink cavities and minimise macro-segregation during continuous casting.
- Production of a maximum slab thickness to allow greater core conditioning during rolling.

ALLOYING STRATEGIES

For high strength low alloy (HSLA) TMCP steels it is important that the carbon content is kept below 0.09% (typically 0.07% or less) thereby avoiding the peritectic reaction during solidification. During this reaction additional shrinkage occurs as a result of the transformation of primary ferrite into austenite, causing inter-dendritic

Steel grade	S355	S355	S460	S460	S460	API X80
Processing route	N	TM	N	QT	TM + ACC	TM + ACC
Plate thickness,mm	50	50	50	50	50	20
C	0.15	0.07	0.15	0.10	0.07	0.03
Si	0.40	0,30	0.40	0.35	0.25	0.30
Mn	1.50	1.50	1.50	1.45	1.55	1.80
P	0.012	0.012	0.012	0.012	0.012	0.012
S	0.004	0.004	0.004	0.004	0.004	0.004
Al	0.03	0.03	0.03	0.03	0.03	0.03
N	0.005	0.005	0.005	0.005	0.005	0.005
Ti	0.015	0.015	0.015	0.015	0.015	0.015
V	none	none	0.12	none	0.04	none
Nb	0.04	0.04	0.04	0.04	0.04	0.10
Cu	none	none	0.60	0.30	none	0.20
Ni	none	none	0.60	0.60	0.25	0.10
Mo	none	none	none	0.25	none	None
CE	0.40	0.31	0.50	0.45	0.36	0.36
PCM	0.23	0.15	0.28	0.22	0.17	0.14

Table 1 **Typical chemical composition, wt% of high strength structural plate**
(N = normalised, TM = thermomechanically rolled, QT = quenched plus tempered, TM + ACC = thermomechanically rolled plus accelerated cooled)

inclusion of liquid steel, which is naturally enriched in alloying elements. As the major alloying element in HSLA steel is manganese and it exhibits a segregation ratio typically twice the bulk steel composition, segregation is often the origin of local brittle zones in the HAZ, resulting in poor toughness. In addition to avoiding the peritectic reaction, the low carbon content also helps to avoid surface cracks during continuous casting.

To help maintain good low temperature toughness, any free nitrogen must be minimised. The addition of the nitride forming elements of aluminium and/or titanium reduces the free nitrogen by the formation of nitrides and also contributes to grain refinement thereby, like Nb, also having a positive effect on toughness. Furthermore, the formation of TiN precipitates also gives control of the grain size in the HAZ and the accompanying inter-critically reheated zones. An important area for the fabricator of high strength steels is the prevention of hydrogen-assisted cold cracking in the weld.

Preheating and post-weld heating are standard precautions against these defects but are timely and costly. Furthermore, there are also practical challenges when undertaking such heat treatments on-site. A comparison of recommended preheat as a function of the plate thickness for some typical combinations of heat inputs as well as hydrogen levels for typical welding processes are illustrated in *Figure 5*[3].

Here, the advantage of using TMCP steels (ie, lower carbon at <0.08%) over normalised steel (ie, higher carbon at 0.18%) is clearly evident, ie, permitting reductions of preheat temperatures or in the main complete elimination of preheat. The curves have been generated for moderately restrained welds and therefore will differ from those calculated from the carbon equivalent formula according to EN 1101-2:2001.

Although all modern TMCP structural steels make use of Nb as the primary microalloying element, the current EN 10025-4 standard only accepts 0.05%Nb maximum. When compared to the recently harmonised linepipe API 5L / ISO 3183 standards, this allows higher levels of Nb to be used as an advantage when C is less than 0.10-0.12% and only limiting the total level of microalloying through Nb+V+Ti <0.15, thereby allowing Nb to be alloyed up to 0.15% in the absence of other microalloying elements.

Therefore, with the known application of lower C (0.03-0.045%) and higher Nb (0.075-0.10%) steels for API X70 (483MPa minimum yield strength) and X80 (552MPa minimum yield strength) linepipe that exhibit excellent low temperature toughness and HAZ CTOD properties, there is a potential revision of the EN 10025-4 specification to permit Nb levels towards 0.10% with a corresponding decrease in carbon content.

A suitable amendment of EN 10025-4 would enable an overall leaner alloy design to be used and also permit much of the experience gained from processing of modern API 5L/ISO 3183 linepipe steels to be transferred across to construction steels. This would also enable steelmakers to quickly adapt the same steel chemistries for two different end applications by suitably adjusting the processing parameters only, bringing additional savings. Furthermore, such modern linepipe grades have also been designed to strain capacity (rather

Structure	Description	High strength steels used
Taipei 101 tower *Taiwan*	509m tall sky scraper, 101 floors above ground, opened in late 2003	95,000t of HSS including TMCP grade SM570M up to 80mm thick (pcm <0.28)
Oresund bridge *Sweden*	7,845m long bridge linking Denmark and Sweden, opened in 2000	82,000t of HSS including grade 65 (S460M) 42-78mm thick. Resultant cost savings of more than $25m
Viaduc de Millau *France*	2,460m long bridge, 270m above ground, opened in 2004	43,000t of HSS including grade S460MC up to 80mm thick and also 120mm thick
Two International Finance Centre *Hong Kong, China*	415m tall sky scrapper, 88 floors above ground, opened in late 2003	90mm thick plate used for six steel-concrete columns from foundation to 6th floor (5,000t) as well as TMCP HSS <40mm.

Table 2 **Recent examples of structures utilising high strength steels**

than a conventional stress-based design) to account for seismic/unstable ground conditions and therefore possess sufficient plastic strain capacity as well as being supplied to within an upper yield ratio.

Table 1 shows typical chemical compositions for 50mm plates, either heat-treated or thermo-mechanically rolled, with the carbon equivalents indicating the necessary conditions for welding. For comparison, an API X80 (552MPa minimum) steel at 20mm plate thickness is also included to illustrate the potential of a lower carbon approach.

SOME RECENT APPLICATIONS OF HSS PLATE

A large variety of construction projects use high strength steels, such as hangars, offshore platforms and sports stadia, however, the most impressive are bridges and skyscrapers, because of their visibility. The merits of modern Nb-bearing high strength plate steels are shown in some recent examples in *Table 2*.

CONCLUDING REMARKS

In recent years the use of Nb-based high strength TMCP structural steels has increased, however, this is coupled with a greater requirement for material performance, such as low temperature toughness, low yield ratios and limiting the need for preheating prior to welding. Modern plate rolling mills are capable of producing heavy plates with yield strengths of 500MPa. To achieve this, along with other performance challenges, cleaner steels are required with lower carbon contents and good management of the hot rolling process with respect to the developing microstructure.

There is an opportunity to accelerate the use of Nb-bearing high strength structural steels based on the experience gained from processing modern API 5L/ISO 3183 linepipe steels (eg, X80 552MPa minimum yield) which can be designed with strain capacity (rather than conventional stress-based design) to account for seismic/unstable ground conditions and therefore possess sufficient plastic strain capacity as well as being supplied to within an upper yield ratio. Such steels exhibit excellent low temperature toughness and HAZ CTOD properties but currently they cannot be applied to structural steels (EN 10025-4) due to limitations in chemical composition.

If the EN 10025-4 specification was revised to permit Nb levels towards 0.10%, a corresponding decrease in carbon content would enable a degree of technology transfer and would also enable steelmakers to quickly adapt the same steel chemistries for two different end applications by suitably adjusting the processing parameters only, thereby making additional savings. MS

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