NIOBIUM IN HIGH STRENGTH WELDABLE BEAMS AND OTHER STRUCTURALS

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Abstract

Niobium is widely applied for the production of high strength structural steels. The evolution of high strength steels is one of the major metallurgical development of the last decades. The competition from other material, in particular reinforced concrete, has without doubt stimulated the progress of structural steels. To maintain the market share of steel, economical fabrication techniques and refined design procedures had to be promoted. This led to an increased interest in steel properties such as weldability and notch ductility.

The last decades have also seen considerable evolution in the profile production processes. The liquid steel is refined either by oxygen or by electric arc furnace steelmaking. Unlike previously for flat products, the usual ingot casting route is more and more being replaced by continuous casting processes. Various types of rolling schedules are now applied for the production of profiles: conventional rolling, normalizing processes and thermomechanical processes.

Niobium is frequently used in the production of profiles either alone or combined with other microalloying elements such as titanium or vanadium. The addition of niobium refines the microstructure and allows a decrease in the equivalent carbon content. This improves the toughness of the steel and its weldability, which is particularly useful for the thickest profile and is also able to attain higher levels of strength. Niobium is particularly attractive in steels with higher nitrogen contents such as those produced by EAF steelmaking: by pinning nitrogen, niobium decreases the free nitrogen content, which is beneficial for the toughness. For such a purpose niobium has an advantage compared to alternatives such as aluminium or titanium in not penalizing the productivity of the continuous caster.

Niobium is also particularly efficient in increasing the strength of steel. The highest strengths are obtained when using thermomechanical processes. Each production process covers a range of grades and thicknesses: above a limiting value, the ductility or weldability requirements are barely satisfied: the widest range is obtained by the application of thermomechanical controlled processes with thickness up to 125 mm in steel grade S460 (65ksi). The use of niobium microalloyed steels allowed the production of high strength beams fulfilling the most severe standards and offering an excellent combination of strength, ductility and toughness both in the hot rolled state and after welding with a wide range of welding energies varying between 8 and 50 kJ/cm. These modern high strength steels offer substantial savings in terms of material and fabrication costs for a wide range of applications such as buildings, bridges and offshore structures.

Nb 2001 Symposium

Introduction

The evolution of high strength steels is probably the most significant metallurgical development of the last decades. Current annual production of these steels which offer an excellent combination of strength, ductility, toughness, formability and weldability at relatively low cost represents approximately 10% of the world market for constructional steels.

A few considerations of metallurgical history are necessary to define the concept of high strength structural steels. In the first part of the 20th century, a single type of steel was used by structural engineers. This steel is commonly designated as "mild steel" which means according to the Oxford English dictionary (1) "mild, soft and easy to work". According to Duckworth and Baird (2), "mild steel" is not deliberately strengthened by alloying elements other than carbon and contains manganese for deoxidization and sulphur stabilization. Mild steels are normally considered to have compositions in the range 0.1 to 0.25% C, 0.4 to 0.7% Mn and 0.1 to 0.5% Si with residuals sulphur, phosphorus and other elements. The yield strength of mild steel is approximately 250 MPa.

Before 1940 the only special requirement for structural steels was for an increased level of tensile strength. To obtain this higher resistance the carbon content was raised to 0.3% with a manganese content of about 1.5%. These steels were not extensively used and do not meet modern requirements for high strength structural steel. They were impaired by the following weaknesses: (a) the yield strength of the steel is too low with value of 360 MPa up to 30 mm thick; (b) there is an excessive drop in yield strength with increasing product thickness; (c) the carbon and manganese contents impair the weldability; (d) the fracture toughness was lower than that of the lower strength steel.

The competition from other material, in particular reinforced concrete, has without doubt stimulated the progress of structural steels. To maintain the market share of steel, more economical fabrication techniques and more refined design procedures had to be introduced. This led to an increased interest in steel properties such as weldability and notch ductility. Basic knowledge was also gained by the investigation of metal failures which had occurred on bridges and in ships such as the well-known "liberty-ships" in the years 1942-1949.

Improvement of the steel properties were mainly obtained by:
- the restriction of the carbon content
- the improvement of the internal cleanliness, including reduction of the sulphur and phosphorus contents
- the use of aluminum treated and micro-alloyed grades combined with normalizing and later thermomechanical rolling

This last development allowed the refinement of the microstructure and the production of stronger and tougher steels.

After 1960, these new steel grades were introduced in revised standards: DIN 17102 in Germany, BS 4360 in the United Kingdom, NF A35-504 in France.
These national standards were used later as a basis for the unified European standard on fine grain steels EN 10113.
Research studies were also carried out aiming to rationalize the selection of steel with resistance to brittle fracture. These studies (3) have linked the usual notch impact test results and the K_{IC} values used in fracture mechanics.
It was demonstrated that more stringent toughness is needed for:
- structural elements under fatigue load
- lower service temperature
- higher yield strength
- thicker products

The new European standards for the design of buildings (4) include such rules as the selection of the temperature with a minimum toughness of 27 Joules and for the selection of the corresponding steel grade.

A strong impetus to produce new structural steels came finally from the development of the offshore industry as in the North Sea area. The offshore sector was searching for superior structural components for the erection of structures in hostile regions with low service temperatures. Due to limited offshore lifting capacity and the development of deeper oil and gas fields, weight saving became of key importance in offshore engineering, putting the focus on high strength steels. Specific standards, as the EN10225 or API 2 MT2, were then defined for these particularly severe applications.

Table I summarizes the specifications of modern structural steel grades.

The production process for sections

The production of long products can be either based on oxygen steelmaking or on electric arc furnace melting. Ingot casting has more and more been replaced by continuous casting processes. Billet, blooms and slab are commonly used as semis and more recently beam blank casting has also been implemented. Near net shape casting for the industrial production of wide flange beams started in 1968 at Algoma using a beam blank casting technology based upon previous BISRA experiments (1964). This technology was then implemented by Japanese producers, Kawasaki Steel followed by Tokyo Steel and NKK, in the USA by Nucor Yamato, Chaparral and Northwestern Steel and Wire and in Europe by ProfilARBED.

To give examples, figure 1 illustrates the various types of semis used for the production of hot rolled sections in the ProfilARBED group. The major profiles are wide flange beams with web sizes up to 1118 mm or flange thicknesses of up to 125 mm. The hot rolled beams constitute a major proportion of the production of structural steels. For this reason the largest part of the following discussion will concern beams but the main principles are valid for other types of sections assuming an equivalent thickness.

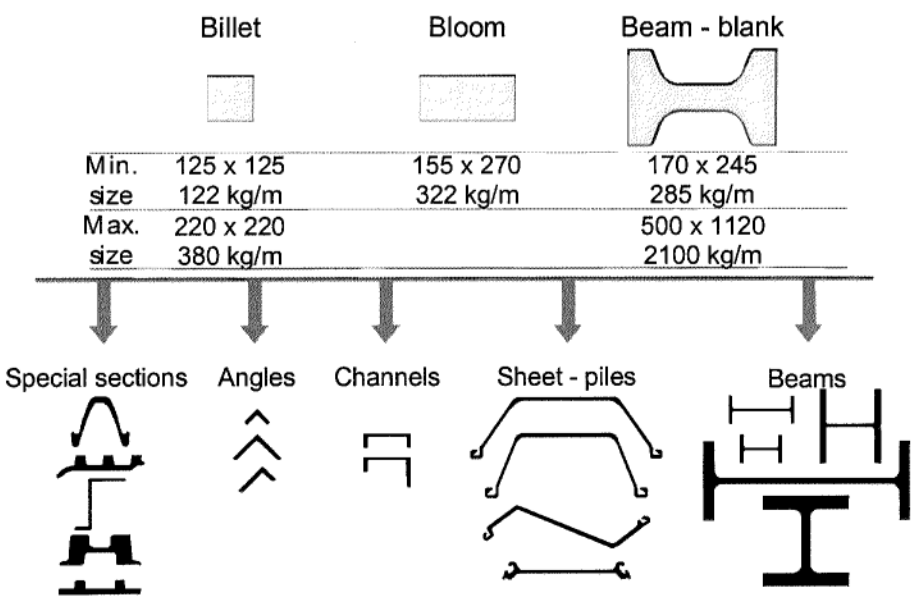

Figure 1: Semis and hot rolled sections

Table I. - Structural steel grades according to European and ASTM standards (sections of 30 mm thickness and unit weight lower than 634 kg/m)

Standard	Grades	Ladle analysis									Tensile test			Impact test	
		C max %	Mn max %	P max %	S max %	Si max %	Al min %	Nb max %	V max %	CE max %	Re MPa	Rm MPa	A* min %	Temp. °C	Energy J
EN 10025 (1993)	S235JR	0,2	1,4	0,045	0,045	-	-	-	-	0,35	225	340-470	26	20	27
	S235J0	0,17	1,4	0,04	0,04	-	-	-	-	0,35				0	27
	S275JR	0,21	1,5	0,045	0,045	-	-	-	-	0,4	265	410-560	22	20	27
	S275J0	0,18	1,5	0,04	0,04	-	-	-	-	0,4				0	27
	S355JR	0,24	1,6	0,045	0,045	0,55	-	-	-	0,45	345	490-630	22	20	27
	S355J0	0,2	1,6	0,04	0,04	0,55	-	-	-	0,45				0	27
EN 10113-3 (1993)	S355M	0,16	1,6	0,035	0,03	0,5	0,02	0,05	0,1	0,39	345	450-610	22	-20	40
	S355ML	0,16	1,6	0,03	0,025	0,5	0,02	0,05	0,1	0,39				-50	27
	S420M	0,18	1,7	0,035	0,03	0,5	0,02	0,05	0,12	0,45	400	500-660	19	-20	40
	S420ML	0,18	1,7	0,03	0,025	0,5	0,02	0,05	0,12	0,45				-50	27
	S460M	0,18	1,7	0,035	0,03	0,6	0,02	0,05	0,12	0,46	440	530-720	17	-20	40
	S460ML	0,18	1,7	0,03	0,025	0,6	0,02	0,05	0,12	0,46				-50	27
EN 10225 (2000)	S355G4	0,16	1,6	0,035	0,03	0,5	0,02	0,05	0,1		345	450-610	22	-20	50
	S355G11	0,14	1,65	0,025	0,015	0,55	0,015	0,04	0,06					-40	50
	S355G12	0,14	1,65	0,02	0,007	0,55	0,015	0,04	0,06			460-620		-40	50
	S420G3	0,14	1,65	0,025	0,015	0,55	0,015	0,05	0,08		410	500-690	19	-40	60
	S420G4	0,14	1,65	0,02	0,007	0,55	0,015	0,05	0,08					-40	60
	S460G3	0,14	1,7	0,025	0,015	0,55	0,015	0,05	0,08		440	530-720	17	-40	60
	S460G4	0,14	1,7	0,02	0,007	0,55	0,015	0,05	0,08					-40	60
A36 (1997)		0,26	0,8	0,04	0,05	0,4	-	-	-		250	400-550	18		
A572 (1997)	Gr50	0,23	1,35	0,04	0,05	0,4	-	0,05	0,15		345	450	18		
	Gr65	0,23	1,65	0,04	0,05	0,4	-	0,05	0,15		450	550	15		
A992 (1998)	Gr50	0,23	1,5	0,035	0,045	0,4	-	0,05	0,11		345-450	450	18		
A913 (1997)	Gr50	0,12	1,6	0,03	0,03	0,4	-	0,05	0,06	0,38	345	450	18	20	54
	Gr65	0,16	1,6	0,03	0,03	0,4	-	0,05	0,06	0,43	450	550	15	20	54

* EN standards: A5d, ASTM standards: A200

Figure 2 is a schematic of the wide flange beam production line of the ProfilARBED plant of Differdange. The liquid steel production is based on the use of the electric arc furnace and continuous casting of beam blanks.

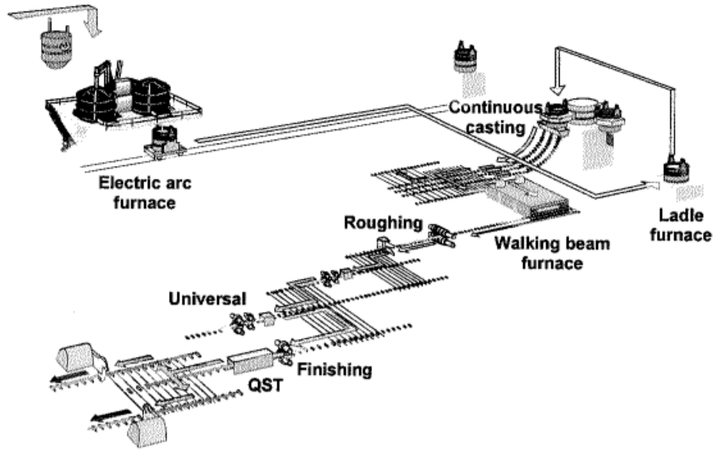

Figure 2: Production line of ProfilARBED Differdange

After casting, the beam blanks are reheated in a walking beam furnace before rolling on a roughing mill and a Grey mill composed of two reversible universal-edger groups and a universal finishing stand. Depending on the rolling mill configuration, different types of rolling schedules are applied for the production of profiles.

Conventional rolling of wide flange beams

The semis are generally reheated at a temperature around 1250°C. (2280°F) The product is hot rolled in 15 to 20 passes. By comparison, 1300°C (2370°F) is used to reheat ingots and 40 rolling passes may be necessary. The flange reduction ranges from 4 to 20 % per pass and the rolling end temperature is higher than 1000°C (1830°F). The temperature is not homogeneous along the profile: the hot points are observed in the web-flange junction and the coldest location is the mid-height of the web. The importance of these variations is related to the size of the profiles and can be as much as 100°C (210°F). With such a rolling schedule an ASTM grain size of 7 in the flanges is typical for a 40 mm thick product.

In order to refine the microstructure titanium-niobium microalloying may be used (5): this ensures a fairly small austenite grain size at the exit of the reheating furnace (50 microns instead of 200-300 microns) and a refined recrystallized microstructure. Laboratory simulation (6) has shown that a deformation of 15% per pass is sufficient to obtain the desired microstructure and mechanical properties of a grade 50 (min. yield strength of 50 ksi, approximately S 355). A typical chemical composition for grade 50 beams is given in table II.

Table II.- Chemical composition (wt. %) of 20 mm beams in grade 50 (finish rolling temperature at 1050°C (1920°F))

C	Si	Mn	P	S	Ti	Nb	(Cu+ Cr+Ni)	N
0.08	0.2	1.5	<0.02	<0.02	0.015	0.022	0.4	0.0085

This alloy design has been successfully applied industrially (7). The high processing temperature during hot working means that all the niobium in this alloy will remain in solid solution and even at the finish rolling temperature no niobium will be precipitated as carbide. Thus, one role of the microalloying element niobium in this product is as solute atom, adding to strength increase via a retardation of transformation, which results in a finer ferrite grain size and a certain amount of bainite in the microstructure. The typical microstructure of this steel consists of about 80% ferrite, the remainder bainite with some pearlite. The ASTM grain size is 9 instead of 7 for a C-Mn steel rolled with a similar rolling schedule. A further strength increase can be expected from NbC precipitates formed in the ferrite during or after transformation. The grain refinement via conventional rolling is nevertheless limited. Therefore for steel with a higher strength than grade 50 and/or thicker than about 20 mm, controlled rolling is necessary to fulfill the ductility requirements.

Normalizing treatment

Normalizing is a heat treatment above the Ac3 transformation point (generally Ac3 + 50°C (Ac3 + 90°F)) carried out to modify the microstructure and consequently the mechanical properties. Normalizing is usually performed on S355 steels containing in the as rolled state a ferrite-pearlite microstructure. The aim is to refine and homogenize this microstructure and to improve the toughness of the steel (8).

The extent of the refining depends on the initial microstructure: most improvements are obtained on products rolled on mills unable to perform thermomechanical rolling, particularly on heavy sections. In the case of a light section no improvement may be observed after normalizing. In these cases, the rolling schedule is considered to act as a controlled rolling procedure, often referred to as "normalizing rolling". This designation suggests that the microstructure and properties of the hot rolled product are similar to what could be expected after a normalizing thermal treatment.

Niobium is frequently used to increase the tensile properties of normalized steels and has the advantage, through a pinning effect of the austenite grain size, to widen the temperature range of the austenizing treatment. This effect is particularly remarkable in silicon killed steels. A niobium content of 0.02-0.04 is sufficient to ensure an ASTM size of 10 whatever is the normalizing temperature between 900° (1650°F) and 1050°C (1920°F). In comparison a silicon killed steel without niobium exhibit an ASTM size of 7 after normalizing at 1000°C (1830°F). The niobium carbonitrides impede the coarsening of the austenite grains as do the aluminum nitrides and are still active at 1050°C (1920°F). This effect is particularly important to ensure a fine ferrite-pearlite microstructure in spite of the thermal heterogeneity of industrial normalizing furnaces.

Table III (9) shows the tensile properties measured on as rolled and normalized wide flange beams. An austenizing temperature of 910°C (1670°F) with a holding time of 30 minutes were used for the normalizing treatment.

Table III. - Tensile properties before and after normalizing treatment
(chemical composition: C,Nb,V see table, Mn 1.3%, Si 0.3%, Al 0.03%, P 0.02%, S 0.02%)

				Tensile properties (MPa)			
Thickness	Chemical composition (%)			As rolled		Normalized	
(mm)	C	Nb	V	YS	TS	YS	TS
40	0,131	-	-	323	484	327	468
40	0,165	-	-	338	515	347	500
60	0,134	0,018	-	330	473	323	474
60	0,157	0,029	-	346	515	343	492
80	0,154	0,018	0,042	323	515	330	484
80	0,18	0,028	0,047	331	523	338	507
80	0,175	0,031	0,053	332	535	348	523
80	0,173	0,027	0,045	321	544	356	511
125	0,18	0,038	0,068	388	607	400	552

The microstructures were measured as ASTM 7 to 9 in the as rolled product depending on the flange thickness. After normalizing ASTM grain sizes of 11 were obtained. The 27J transition temperature of the rolled product gets improved by more than 40°C (105°F): after normalizing a transition temperature below –45°C (-50°F) is obtained. A limited decrease of the tensile properties is commonly noticed after normalizing as observed for most of the tensile strengths reported in table III.

Based on these results the following alloying concept (figure 3) can be proposed to produce S355 steels.

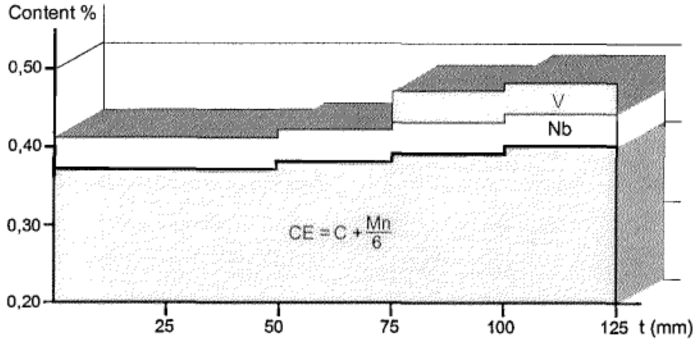

Figure 3: Steel-alloying concept for normalized S355 steels

In comparison with the thermomechanically-rolled steels, the higher carbon equivalent content penalizes the production of S460 grades, attempting to fulfill the weldability requirements.

It must also be noted that the thermal treatment induces deformation of the profiles, particularly for the lighter sections. These deformations have to be corrected by straightening machines.

Thermomechanical processing: controlled rolling

An excellent combination of strength and impact properties can be obtained in niobium-treated sections if rolling can be controlled in such a way that a significant amount of deformation occurs in the lower austenite region. In this process the austenite is first deformed in a temperature range above 1050°C (1920°F) in order to refine the austenite grain size. If given a total deformation of around 70 % a fine austenite grain size is formed by static recrystallization after each pass.

This partially rolled section is then held until the temperature is below about 900°C (1650°F) when the finishing passes are given. Since recrystallization is sluggish in niobium treated steel the austenite grains become pancaked leading to significant grain refinement.

The improvement in properties is particularly spectacular for steels with high free nitrogen contents as in silicon killed steels produced by electric arc furnaces (10). In these steels the total nitrogen content can be higher than 100 ppm. The free nitrogen content of the air cooled silicon killed steels has been demonstrated to be proportional to the total nitrogen content:

$$N_{free} = 0.43\ N_{tot} \quad (1)$$

The toughness of the silicon killed steel depends on the free nitrogen content: a good level (TT40J~-10°C (15°F)) is obtained with a free nitrogen content below 32-33 ppm. It rapidly deteriorates (TT40J>+30°C (90°F)) when the free nitrogen content exceeds a threshold which is around 35 ppm.

To improve the toughness, the following processing steps are effective:

- to lower the end rolling temperature of the C-Mn steel from 960°C (1760°F) to 870°C (1600°F). Thereby, the mean ferrite size is refined to ASTM 9 instead of 7; this modification improves significantly the steel toughness (figure 4)
- the steel toughness is optimized by combining the application of a thermomechanical rolling scheme and the addition of nitride forming elements able to lower the free nitrogen content (figure 5)

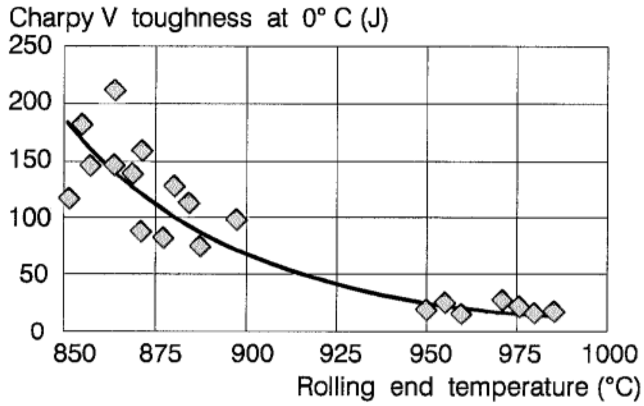

Figure 4: Influence of the rolling scheme on toughness of silicon killed EAF steels

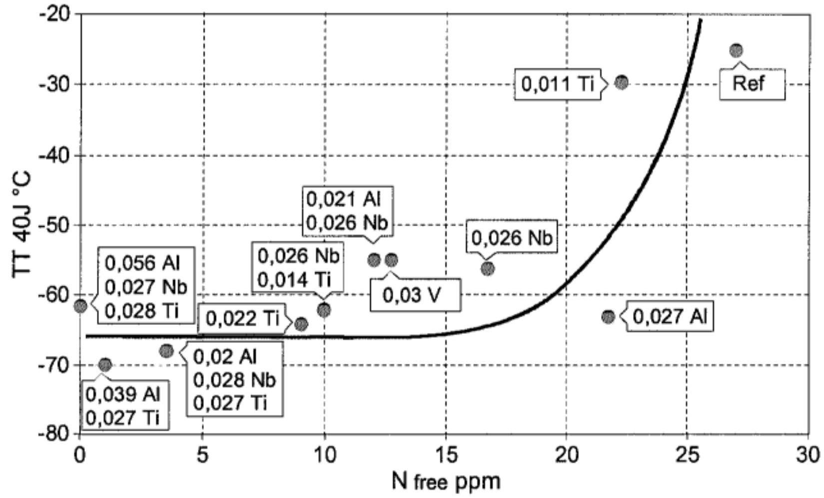

Figure 5: Toughness of thermomechanically rolled steels in function of the free nitrogen content

Together with controlled rolling the reduction of the free nitrogen content below 20 ppm allows the 40 J transition temperature to be lowered below –50°C (-60°F).

Aluminium is commonly used in flat products to reduce the free nitrogen content. Other chemical elements such as titanium, niobium and vanadium can also be used. Vanadium and niobium have the advantage compared to aluminum and titanium not to be the source of castability problems in continuous casting such as nozzle clogging or increased breakouts (11, 12). Measures of the free nitrogen content (by internal friction analysis) have allowed the determination of the efficiency of the nitride forming elements. This has led to the establishment of a relationship to compute the so-called "equivalent aluminium":

$$Aleq = Al + 2Ti + Nb + V \qquad (2)$$

(contents in weight %)

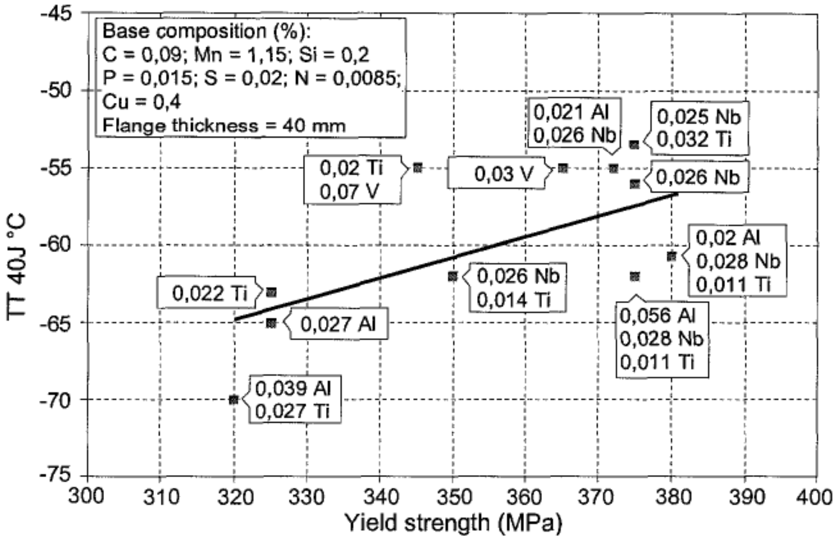

Figure 6: Toughness and yield strength of thermomechanically hot rolled steels

The choice of the alloying elements can be related to the aim mechanical properties of the beams. This is illustrated in figure 6 in which the toughness (TT 40 J) of the steels is plotted as a function of the yield strength. A value of TT40J between –60°C and –70°C (-80°F and -95°F) is obtained with a yield strength of ~ 320 MPa for the steels alloyed with aluminium, titanium, aluminium+titanium and titanium +vanadium,. The strength is similar to the reference C-Mn steel which testifies tothe lack of precipitation hardening. A yield strength of 375 MPa with TT 40 J of –55 °C (-70°F) is obtained for the niobium microalloyed steels in which niobium brings a clear hardening effect due to the precipitates and the refinement of the microstructure. The steels with combined titanium/niobium, microalloying may exhibit a slightly reduced hardening due to the interaction of TiN precipitation with niobium.

Similarly the addition of titanium to a vanadium microalloyed steel reduces the hardening effect of vanadium due to the nitrogen fixed by the titanium which reduces the hardening effect of the vanadium nitrides. These considerations are used in figures 7 and 8 to compute the yield and tensile strengths of the microalloyed steels as a function of the microalloying contents.

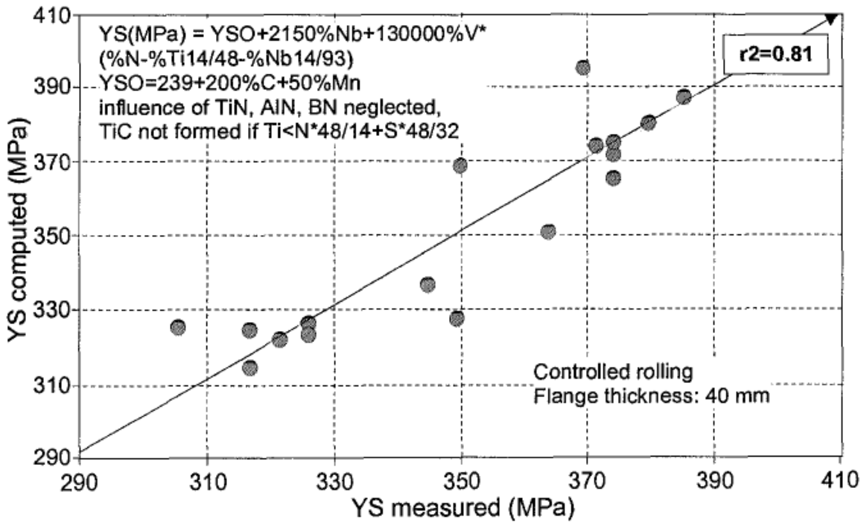

Figure 7: Comparison of calculated and actual yield strengths of microalloyed steels following thermomechanical rolling

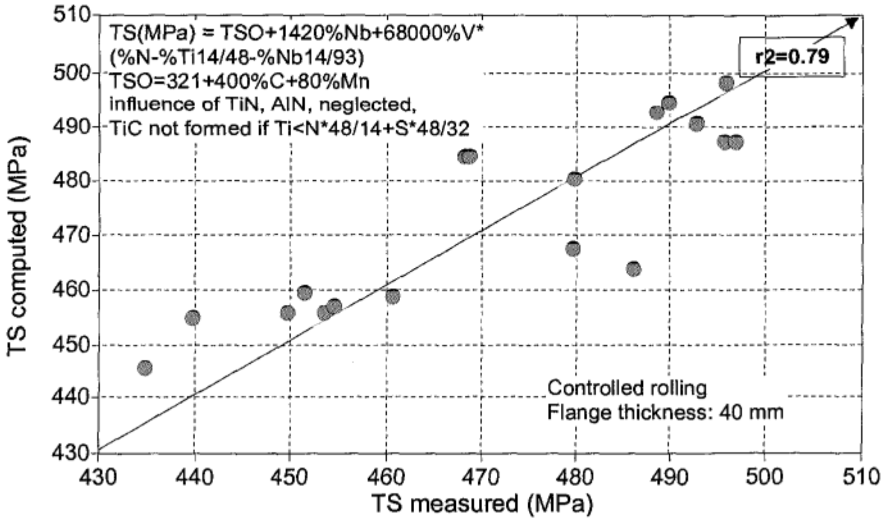

Figure 8: Comparison of calculated and actual tensile strengths of microalloyed steels following thermomechanical rolling

Although controlled rolling of sections leads to an attractive combination of strength and ductility it also includes substantial disadvantages. The reduction of the rolling temperature brings an increase in rolling loads and many mills are not designed to resist the additional stresses. Moreover the presence of niobium in a temperature range in which the recrystallization kinetics are reduced increases rolling loads compared to those of C-Mn steels. Because a waiting time is usually incorporated in the rolling schedule, controlled rolling can increase rolling times and reduce productivity.

Figure 9 shows the necessary chemical composition, carbon equivalent and niobium content, in order to obtain the required tensile properties of S355 as a function of the flange thickness. To obtain the required tensile properties various chemical compositions can be used and Figure 10 shows another steel alloying concept (13) used to produce S355 grades.

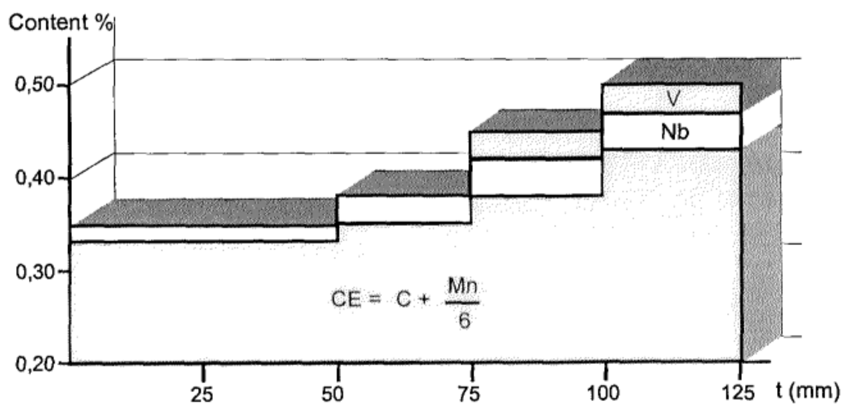

Figure 9: Steel alloying contents for S355, controlled rolling

In comparison with the concept presented in figure 9, the carbon content is increased by 0.06 % and the niobium (vanadium) content is lowered. Similar tensile properties are obtained with these two compositions. However , a strong influence on toughness is observed. The toughness in the length direction is improved in the lower carbon, niobium-microalloyed compositions (figure 11). Figure 11 also confirms that the toughness requirements are more difficult to satisfy with the increase in thickness.

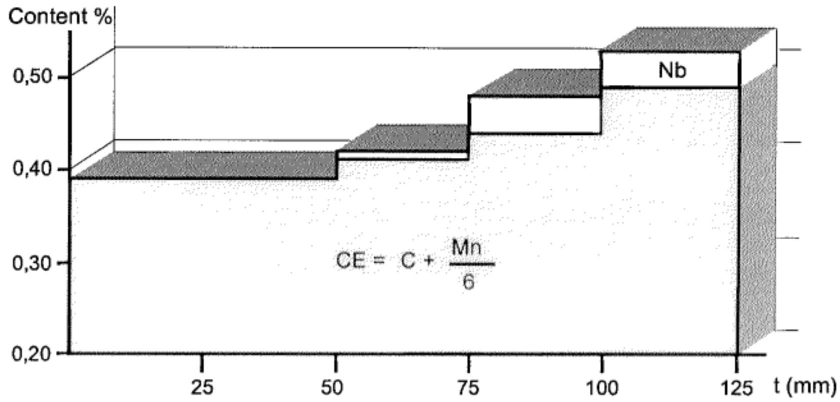

Figure 10: Alternative steel alloying concept for S355

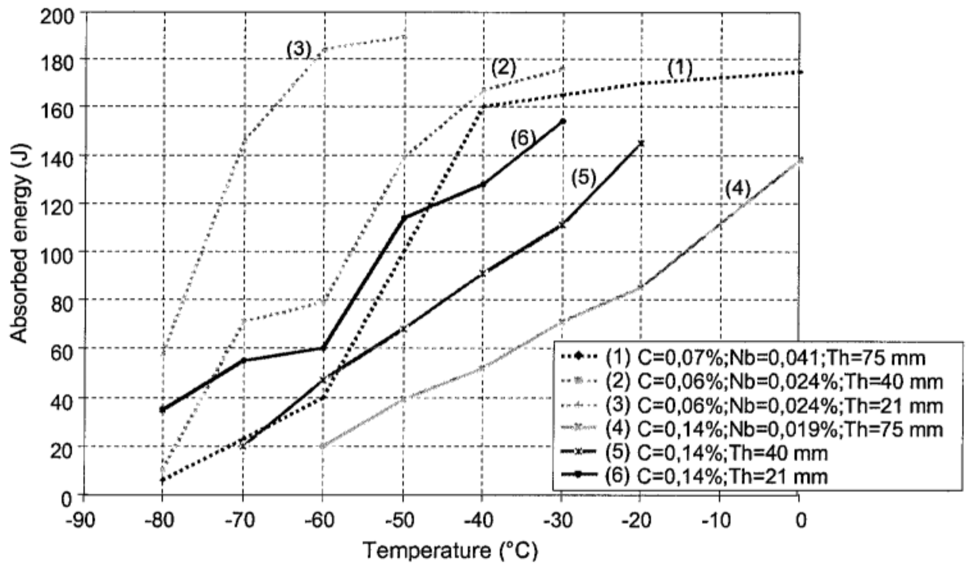

Figure 11: Charpy V toughness in longitudinal direction
(base chemistry: Mn=1.4%, P=0.02%, S=0.01%, Si=0.3%, Al=0.03%)

Other ductility requirements may also be imposed in the most severe standards such as the EN 10225 related to weldable structural steels for offshore structures. It concerns the toughness in the transverse direction or the through-thickness ductility. The toughness in the transverse direction is slightly improved in the lower carbon steel but the major effect, as for the through thickness ductility, is obtained by lowering the sulphur content (table IV and figure 12).

Table IV. – Value for the reduction of area in the through thickness direction (S355 grade, base chemistry: C=0.06%; Mn=1.4%; P=0.02%, Si=0.3%, Al=0.03%, Nb=0.025%)

Thickness (mm)	Sulphur content (%)		
	0,005	0,012	0,030
21	74	53	18
40	72	50	25

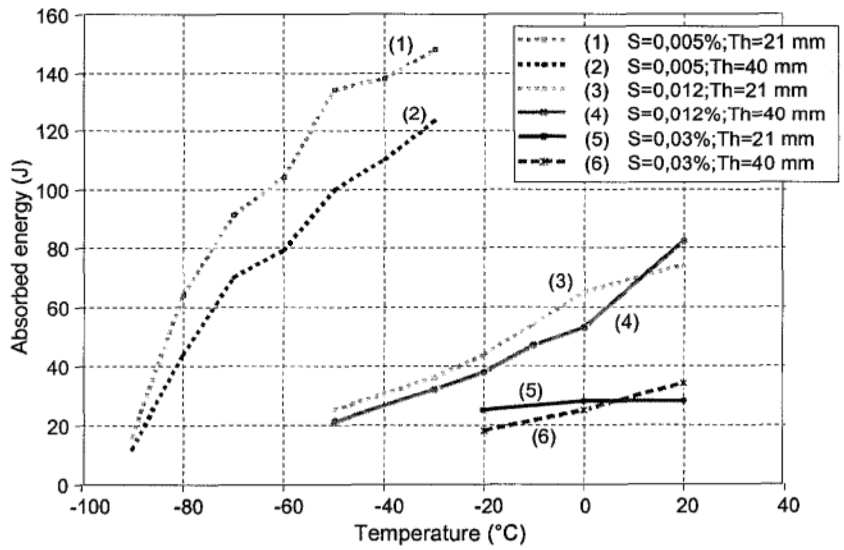

Figure 12: Charpy V toughness in transverse direction (S355 grade, base chemistry: C=0.06%; Mn=1.4%; P=0.02%, Si=0.3%, Al=0.03%, Nb=0.025%)

The thermomechanical rolling procedure is also used to produce sections in S460 grade. However, this process does not cover the highest thickness range.

With higher thicknesses the rolling temperature increases and the cooling rate after rolling decreases thus causing coarser microstructures. To obtain the required tensile properties the alloying content has to be amended . Due to weldability requirements and the limit in carbon equivalent, beams in grade S460 are not produced for thicknesses higher than 50 mm. (figure 13)

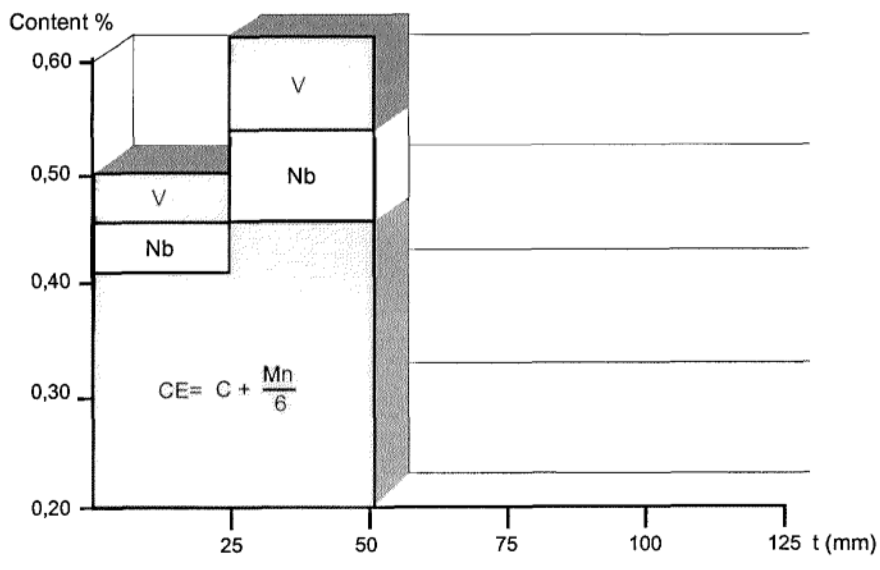

Figure 13: Steel alloying contents for S460, controlled rolling

Thermomechanical processing: accelerated cooling

To overcome the limitations of the thermomechanical rolling, accelerated cooling of beams after rolling has been developed by ProfilARBED in collaboration with the Centre de Recherches Metallurgiques and British Steel plc.

In the QST process (Quenching and self-tempering) an intense water cooling is applied to the whole surface of the beam directly after the last rolling pass. Cooling is interrupted before the core is affected by quenching and the outer layers are tempered by the flow of heat from the core to the surface. Figure 14 illustrates this treatment schematically. At the exit of the finishing stand directly at the entry to the cooling bank, temperatures are typically 850°C (1560°F). After cooling over the whole surface of the section a self-tempering temperature greater or equal to 600°C (1110°F) is aimed for.

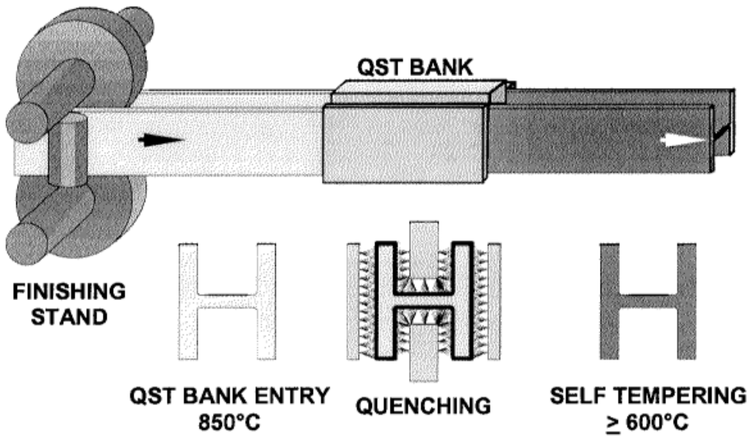

Figure 14: QST process applied on beams in the rolling heat

A prerequisite for a uniform QST treatment is a homogeneous temperature profile of the beam section before entering the cooling bank. This condition is fulfilled by applying selective cooling during rolling to the hottest part of the beam, namely the flange-web junction . Figure 15 gives a view of this process. By applying this selective cooling in the region of the flange web junction the temperature difference can be eliminated as the comparison between typical temperature profiles over the flange width illustrates. Figure 16 shows the operation of the QST process after the exit of the finishing stand.

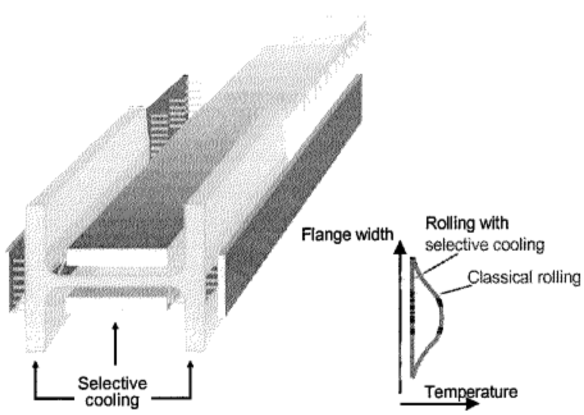

Figure 15: Influence of selective cooling during rolling on the temperature profile of the flange width

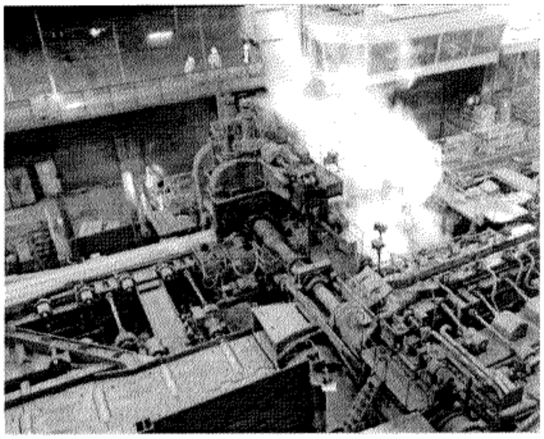

Figure 16: QST process in operation

A similar process has been developed as the Super OLAC S (Online accelerated cooling) by NKK at the large section mill of Fukuyama works. This system was derived from the OLAC device traditionally used since 1980 in plate production (14). The application to large shapes has been hampered by technical difficulties linked to the cross-section complexity of the shapes. Cooling without deformation due to heat distortion has been a challenge and achieving product quality has been difficult due to the wide diversity of sizes and grades.

The development of an accelerated cooling device for wide flange beams was also reported by Nippon steel (15).

Figure 17 illustrates the different types of rolling schedules applied and the resulting microstructures of the hot rolled products. As already stated, typical ASTM grain sizes after conventional rolling are about 7. This value reaches around 9 with a controlled rolling procedure and 11 with the use of the accelerated cooling device.

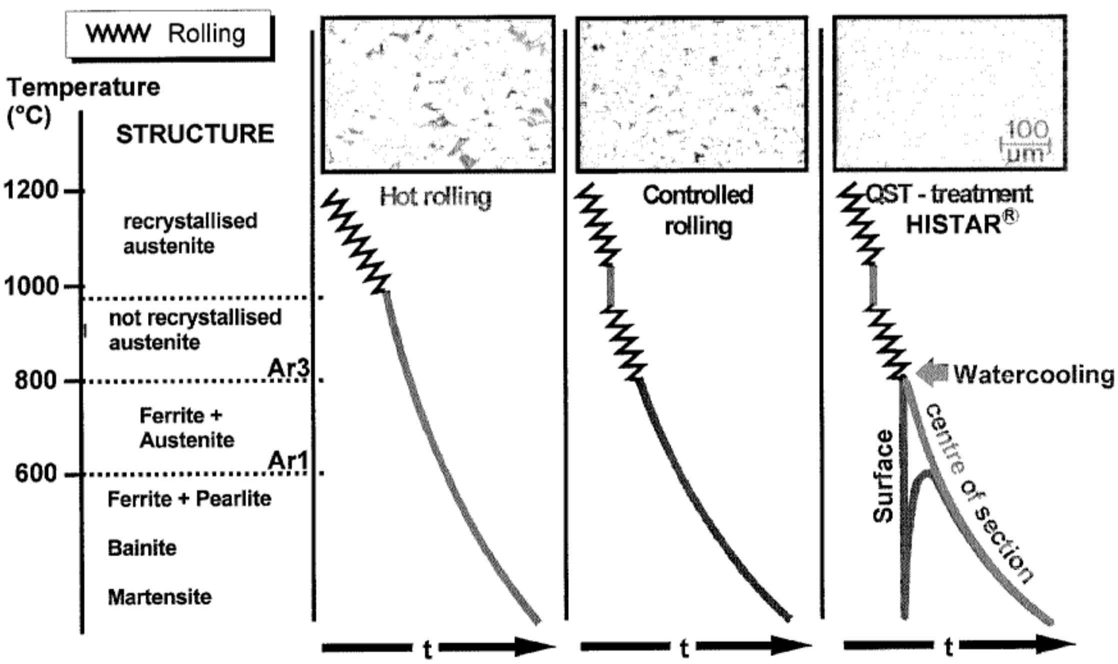

Figure 17: Comparison of the different rolling process for beams

Such a fine microstructure allows the attainment of toughness requirements at very low temperatures: following the specifications of EN 10113, transition temperature at 41 J below –50°C (-60°F) are reached for thicknesses up to 125 mm.

Due to this strong cooling rate refinement no supplementary refinement is obtained by the addition of niobium. Thus no significant improvement in toughness can be realised by the addition of niobium to the hot rolled product. Nevertheless niobium is added to high strength steels to allow a reduction of the carbon equivalent for weldability reasons. This is especially the case for the thicker products. Figure 18 shows the necessary chemical composition, carbon equivalent and niobium content, in order to obtain the required tensile properties with flange thicknesses up to 125 mm.

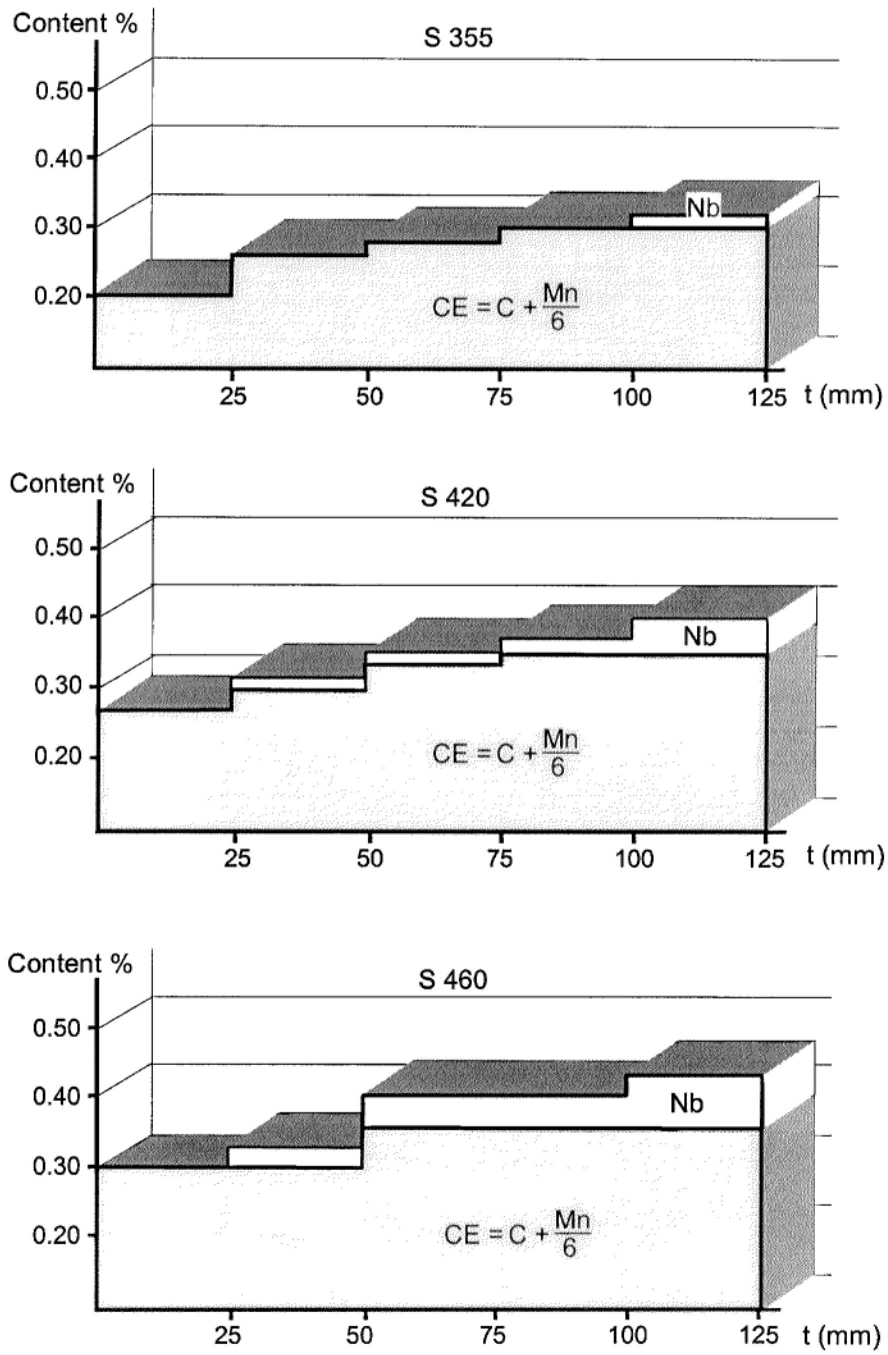

Figure 18: Steel alloying concept for the production of QST structural shapes

Effect of the chemical composition on the mechanical properties

The increase of the yield and tensile strength with carbon, manganese and niobium contents can be roughly summarized by the coefficients of table V derived from industrial experiments on wide flange beams. The most remarkable effects are observed following the thermomechanical process and particularly with the use of accelerated cooling.

Table V. - Increase of the yield and tensile strength in MPa / % as a function of the alloying elements and production process (wide flange beams, 40 mm flange thickness)

	Yield strength (YS) and tensile strength (TS) increase in MPa / %							
	Conventional		Normalized		Thermomechanical		QST	
	YS	TS	YS	TS	YS	TS	YS	TS
C	250	500	260	260	200	400	460	275
Mn	50	65	41	41	50	80	250	170
Nb	1000	500	1000	1000	2150	1420	2000	2000

The toughness of structural steels is essentially dependent on the microstructure and chemical composition. The following relationship is extracted from the works of Mintz et al (16), for aluminum killed structural steels with ferrite-pearlite microstructure.

$$54\ J\ TT\ (^\circ C) = 84.8 - 5.65d^{-0.5} + 1.67\%pearlite - 53.1\%Si + 1490\%S - 1379\%P - 70.1\%Mn - 4.97CR^{0.5} \quad (3)$$

with: 54 J TT = 54 Joules transition temperature, d = ferrite grain size in mm and CR = cooling rate in °C/min . The equation highlights the favourable effect on toughness of grain refinement, increased manganese content and cooling rate after rolling. The equation quantifies the negative effect of the pearlite content. The work of Irvine et al (17) has also demonstrated the strong detrimental effect of free nitrogen.

These considerations are taken into account together with weldability requirements to optimize the chemical composition. The best combination of yield strength and toughness is obtained with a high manganese content of approximately 1.5% and reduced carbon content. The reduction in carbon content is compensated by the addition of microalloying elements in particular niobium which provides several advantages: reduction of the free nitrogen content, refinement of the microstructure and a reduced effect on toughness with increases in strength.

Weldability

A detailed discussion of the welding of niobium bearing HSLA steels is presented by Batte et al (18). Complementary data concerning the welding of structural steels are given below.

The usual welding instructions define the operating conditions in order to avoid the occurrence of cold cracking. Cold cracking is due to an insufficient ductility in the heat affected zone and is enhanced by free hydrogen from the welding consumables. The main parameters determining the appearance of hard and brittle zones are the hardenability of the steel and the cooling rate after welding. To describe the influence of the base steel chemistry on the cold cracking susceptibility various function have been proposed such as the carbon (CE) equivalent or composition parameter P_{cm} :

$$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15 \quad (4)$$

$$P_{cm} = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B \quad (5)$$

In order to avoid cold cracking after the welding of profiles, the welded assembly is preheated to a temperature defined by the following parameters:

- the carbon equivalent content
- the product thickness
- the hydrogen content of the welding consumables
- the welding energy

This preheat temperature is computed following the method described in procedures such as the AWS D1.1, EN 1011 or SEW088. Although such a method can be used to determine a preheat level, another important value to determine the minimum heat input, such as the minimum size of single-pass fillet welds, that can be deposited without preheat.
The first advantage of the substitution of a C-Mn steel by a lower carbon niobium-microalloyed steel is thus to extent the range of processing conditions that can be used without preheating needs while avoiding hard brittle zones.

Figure 19 shows a typical example of a hardness profile of a butt weld in a S460 grade microalloyed with niobium. The chemical composition was (%): C=0.08, Mn=1.38, P=0.01, S=0.002, Si=0.2, Al=0.044, Nb=0.043.

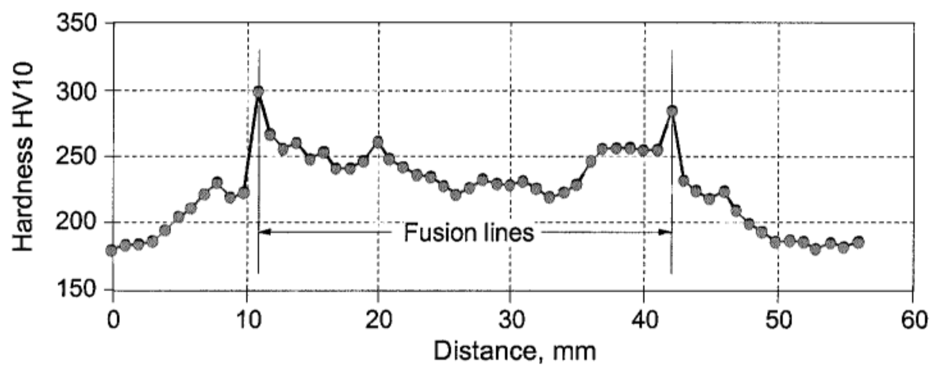

Figure 19: Hardness profile at mid-thickness for a ½ V, butt weld, FCAW 8 kJ/cm

The wide flange beams were welded with a very low heat input (8 KJ/cm, FCAW) and without preheating. The hardness profiles across the weld joints were carried out at different locations with respect to the thickness and showed that all values were below 300 HV10.

In order to check the influence of welding on the steel properties, steel sections have been butt-welded. All the welding was performed without preheating. The steel compositions are given at the table VI.

Table VI.- Chemical composition (%) of steels used for weldability evaluation

		Chemical composition (%)							
Type	Grade	C	Mn	P	S	Si	Al	Nb	N2
C-Mn	S355 J0	0.15	0.69	0.029	0.012	0.18	0	0.007	0.009
Nb	S355 J2	0.07	1.14	0.015	0.018	0.16	0	0.033	0.009

The following processing conditions were used:

- thermomechanical rolling with accelerated cooling
- flange thickness 25 mm
- welding process: SMAW

- joint type: butt weld , bevel oxygen-cutting K
- weld axes perpendicular to the rolling direction
- no preheating
- multi-pass welding with heat input of 10-12 kJ/cm

As already shown (figure 11), the introduction of lower carbon microalloyed steels had a favourable influence on the toughness of the hot rolled products.

The characterization of the welds shows that the tensile properties are not impaired by welding. The toughness deteriorates (figure 20) but the advantage of the niobium microalloyed steel is preserved in the base metal and close to the fusion line.

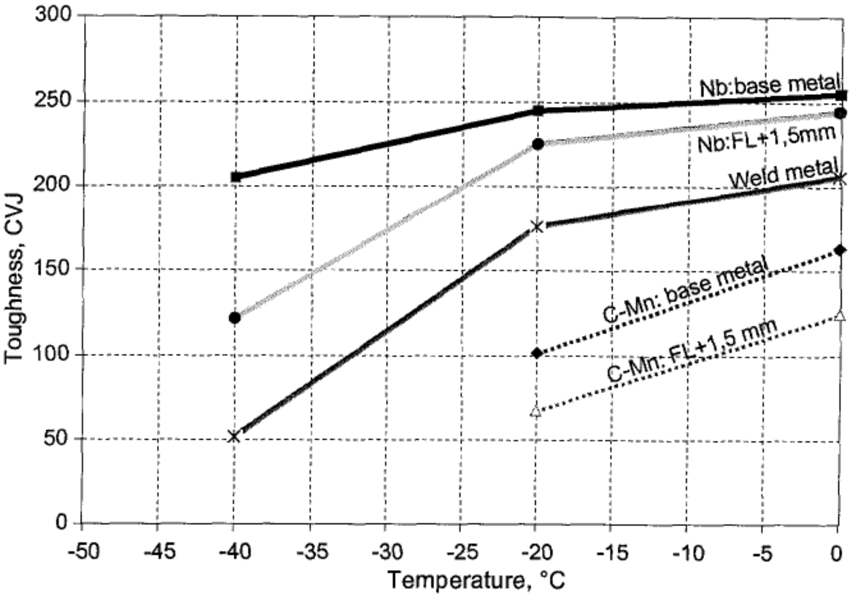

Figure 20: Longitudinal Charpy V notch toughness of S355 steel – base metal and SMAW welding

It should be noted that the literature reports a negative effect of niobium and vanadium on the toughness, especially in high heat input welding. This embrittlement would be due to the promotion of brittle microstructure or carbonitride precipitation. This situation is nevertheless not common as the usual welding process of sections (multi-pass SMAW, MAG or FCAW) currently use relatively low welding energy of 12 to 20 KJ/cm.

Higher welding energies were tested (19) on S460 offshore grade with niobium microalloying. The chemical composition was (%): C=0.08, Mn=1.38, P=0.01, S=0.002, Si=0.2, Al=0.044, Nb=0.043.

The wide flange beams (W360*410*463) were processed using thermomechanical rolling followed by a QST treatment.
The following processing parameters were used:

- thermomechanical rolling with accelerated cooling
- flange thickness 57 mm
- welding process: SAW
- joint type: butt weld , bevel oxygen-cutting 1/2V
- weld axes parallel to the rolling direction
- no preheating
- multi pass welding with heat input of 35 and 50 kJ/cm

Tests were performed to evaluate the mechanical and technological properties according to the standard EN10225 concerned with weldable structural steels for fixed offshore structures. Charpy transition curves have been performed at cap, mid-thickness and root for various positions with respect to the fusion line (FL): FL-2 mm (weld metal), FL, FL+2 mm and FL+5 mm. The overall results show, that the minimum requirements of 47 J at - 40°C (-40°F) are largely fulfilled down to - 60°C (-80°F). The SAW process with the high heat input of 50 kJ/cm did not show any brittleness at the fusion line. Figure 21 shows examples of these results.

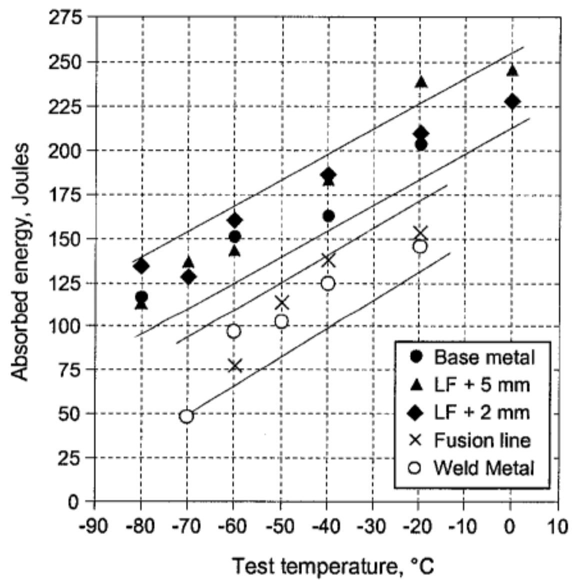

Figure 21: Transverse Charpy V notch toughness, SAW weld assembly 50 kJ/cm, weld root

A fracture toughness evaluation was also performed using a full thickness CTOD test. This test originally developed in England for welded structures follows the Crack Tip Opening Displacement and determines the critical value of the crack corresponding to brittle propagation. The location and dimensions of the samples are indicated in figure 22. The tests were performed with the notch located in the following position: Weld Metal (WM), Grain Coarsened Heat Affected Zone (GCHAZ) and Intercritical Heat Affected Zone (ICHAZ).

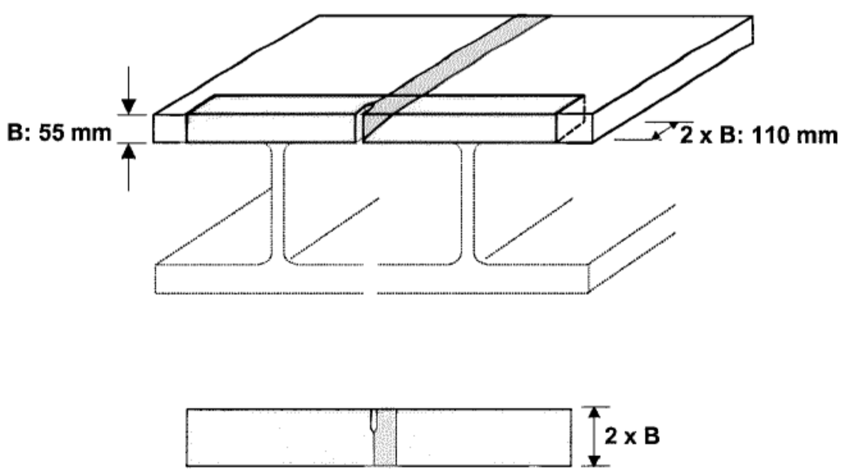

Figure 22: Position and dimensions of CTOD specimens in the butt weld assemblies. Notch positions: weld metal, GCHAZ, ICHAZ

Figure 23 shows that the HAZ maintains a high level of fracture toughness. In all cases the results were better than the minimum of 0.25 mm at –10°C (15°F) prescribed in the EN10225. Other types of test such as bending, wide plate or CTS have also been performed and confirm the excellent behaviour of these high heat input welds.

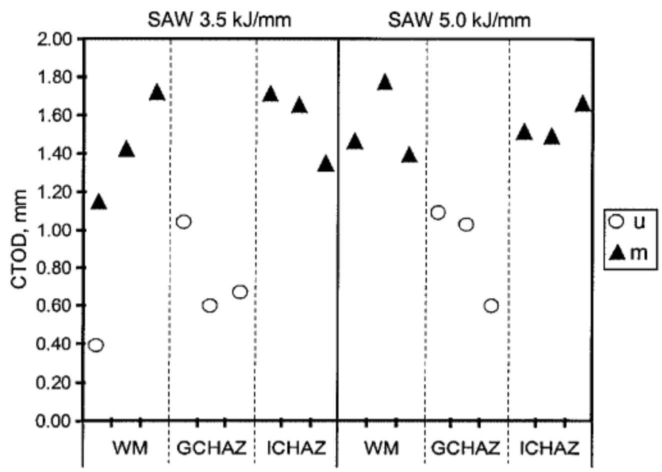

Figure 23: CTOD (-10°C) test results on welds. Notch positions: weld metal (WM), GCHAZ, ICHAZ. Crack propagation type: u = unstable, m = stable growth, no critical propagation

Applications of high strength structural steels

The profiles presently produced in high strength steel grades cover yield strengths ranging from 345 to 460 MPa, following the main standards quoted in table I. The use of high strength steels allow an increase in the load or a decrease in the weight of the structure at constant load. The weight gain derived from the introduction of high strength steel depends on the type of section and loading mode.
Limitations in using high strength steels for structural applications are that yield strength is not the only main design factor. Other critical factors are deflection and instability phenomena such as buckling. These phenomena are dependent on Young's modulus and the geometry of the profile rather than yield and tensile strength (20).

Figure 24 shows the advantage of using high strength steel for columns in structures. By comparing 3 European sections with an identical design load but with 3 different geometric cross sections in three different steel types, S460 (ReH min. = 460 MPa), S355 (ReH min. = 355 MPa) and S235 (ReH min. = 235 MPa), the advantages of the high strength steel are obvious. Considering the use of S355 steel as state of the art, it can be concluded that S460 leads to a 14 % weight saving and S235 to 32 % weight increase compared to S355. In terms of material costs the savings for S460 are about 10 % compared to S355 and 25 % compared to S235.

The use of these high strength steels in the building industry also offers substantial advantages in terms of fabrication cost, in particular through the reduction in the volume of welded metal. Figure 25 shows for example in the case of beams used for welded trusses the savings in weight and amount of weld metal brought about by the substitution of S235 grades by high strength steels.

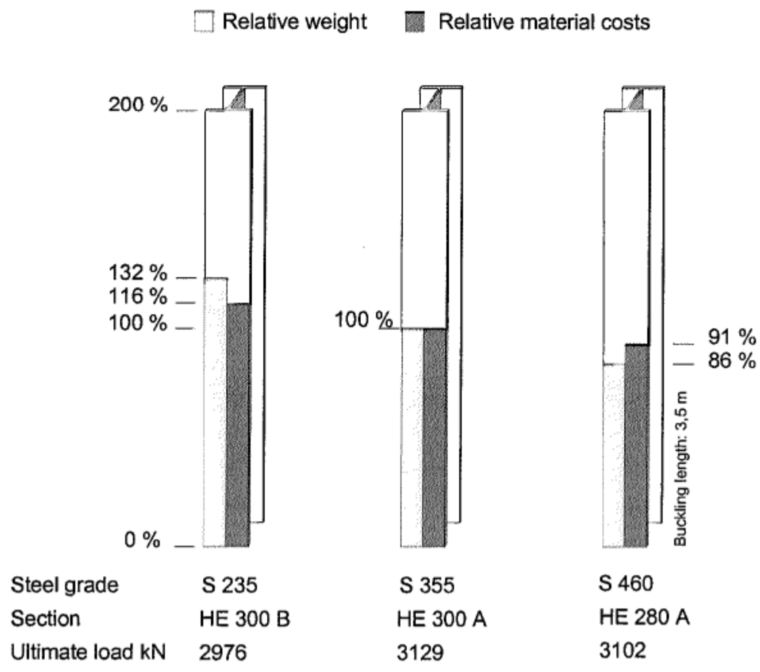

Figure 24: Weight savings using high strength grades compared to conventional steel qualities

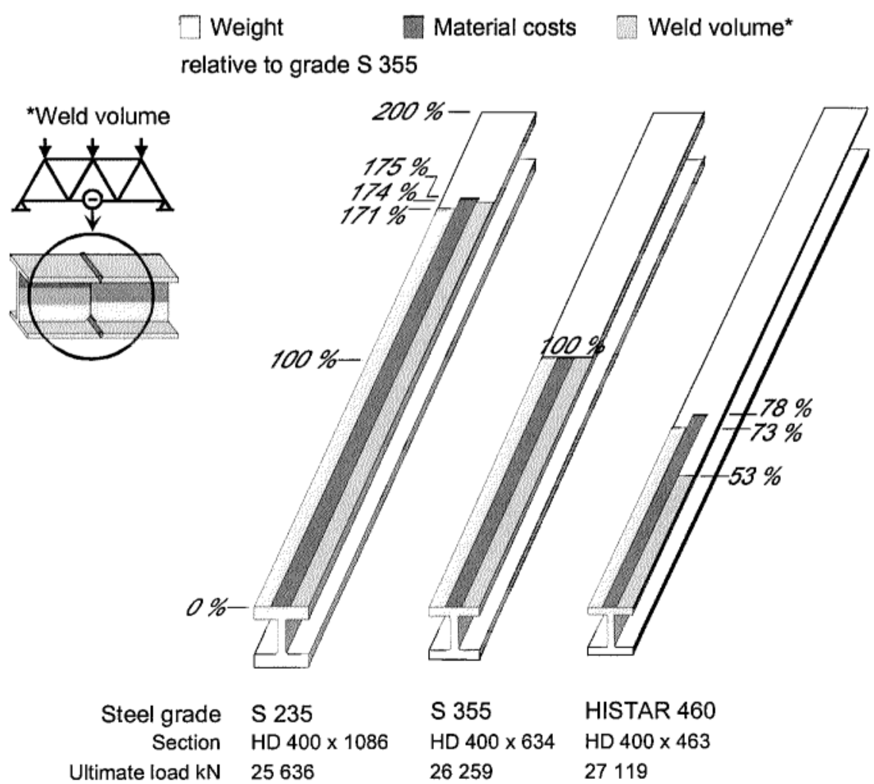

Figure 25: Weight, material cost and weld volume savings of high strength steels compared to conventional structural steels

Considering again the use of S355 steel as the state of the art, S460 leads to a 25 % weight saving and S235 to a 70 % increase compared to S355. A similar comparison based on material costs leads to about 20 % cost saving when using S460 instead of S355. By calculating the weld volume needed for splicing 2 tension members, thanks to lighter sections, the use of higher strength steel leads to a 50 % weld volume saving which reflects directly on fabrication costs.

Other smaller savings, related to the weight advantage are due to a reduced cost of erection, handling or transport. Finally there is also a space gain, due to the smaller depths of girders or columns.

Due to the limitations in stability and deflection in combination with a material price that increases with increasing yield strength there is an optimum choice of steel grade depending on the application: the optimum yield strength level usually lies in the range of yield strength from 355 to 460 MPa.

Conclusions

The use of modern production processes combined with microalloying additions has allowed the development of stronger, tougher and easily weldable structural steels even for the thickest sections.

Niobium in particular is widely used for the production of structural steels as it offers substantial advantages: no impairment of the castability, refinement of the microstructure, reduction in free nitrogen content, effective increase in tensile properties and good weld properties.

The use of these modern high strength steels for the erection of structural components offers substantial savings in terms of material and fabrication costs for a wide range of applications such as buildings, bridges and offshore structures.

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