5 High-Performance Steels in Europe

5.1 Production Processes, Mechanical and Chemical Properties, Fabrication Properties

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5.1.1 Introduction

Since the first application of steel in steel structures in the 19th century the development of steel construction has been closely linked to the development 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. Especially with the application of "new" production processes for carbon steels such as the thermo-mechanical rolling and the quenching and tempering process, steel with a high construction strength but guaranteeing also good fabrication properties such as weldability was introduced into the construction market. Today, the application of these grades is driven by the following major reasons:

- Economy: By increasing the strength of steel, the structural section can be reduced depending on the structural problem. This may reduce fabrication and erection costs – an important task in high-wage economies.
- Architecture: The size of structural elements can be reduced, enabling special aesthetic and elegant structures, which embed in the environment in an outstanding manner.
- Environment: Construction with less steel means also a reduced consumption of our world's scarce resources.
- Safety: Modern high strength steel grades exhibit not only high strength values. Special grades combine this strength with excellent toughness so that a high safety both in fabrication and application of the structures is ensured. In particular, modern offshore steel grades performing at some of the lowest service temperatures are a good example.

It should not be neglected that several other branches started with the application of high strength grades earlier. Mobile crane construction uses today steel grades up to a yield stress of 1100 MPa; in the offshore industry thermo-mechanically rolled steels in higher strength classes are likely to be the steel group the most often used for cold water applications. Even the shipbuilding industry has started to design with high strength steel. Nevertheless, this article focuses on the steel grades which are today used in steel construction (bridges, buildings, hydraulic steelwork) in Europe although we know that engineers in this field can profit a lot from the good experience made in other branches.

5.1.2 Production Processes for High-Strength Steel

The development of new steel grades was always driven by the demand of the users wanting materials exhibiting 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 and the historical context is shown in Fig. 5.1.1. Until 1950 the steel which is today known as S355J2 according to the European standard EN 10025 was regarded as high tensile steel. As a plate this grade is usually produced by conventional hot rolling (see Fig. 5.1.2, process A) followed 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 slow cooling resulting in a fine and homogeneous grain structure (see Fig. 5.1.2, 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.

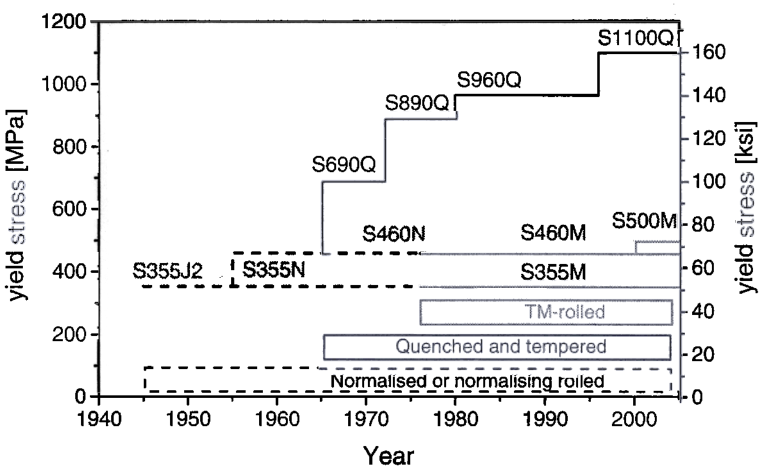

Fig. 5.1.1: Historical development of production processes for rolled steel products

During the 1960s 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 rapid cooling, normally in water, plus a subsequent tempering below Ar_1 (temperature where austenite begins to form. See Fig. 5.1.2 process C). Roughly speaking during the first step a "strong" martensitic or bain-

titic grain structure is obtained whose toughness properties are significantly improved during the tempering process. See Fig. 5.1.3. Besides this heat treatment the good balance between strength and toughness is based on the fact that these steels are alloyed by adding micro-alloying elements (niobium, vanadium, titanium) precipitating as finely distributed carbonitrides.
Today this process gives steel grades with yield strength up to 1100 MPa, although only grades up to 960 MPa yield stress are standardised. Furthermore, classical European steel construction, i.e. buildings and bridges, profits only very rarely from this "ultra-high" strength steel and is mostly limited to steel grades up to S690.

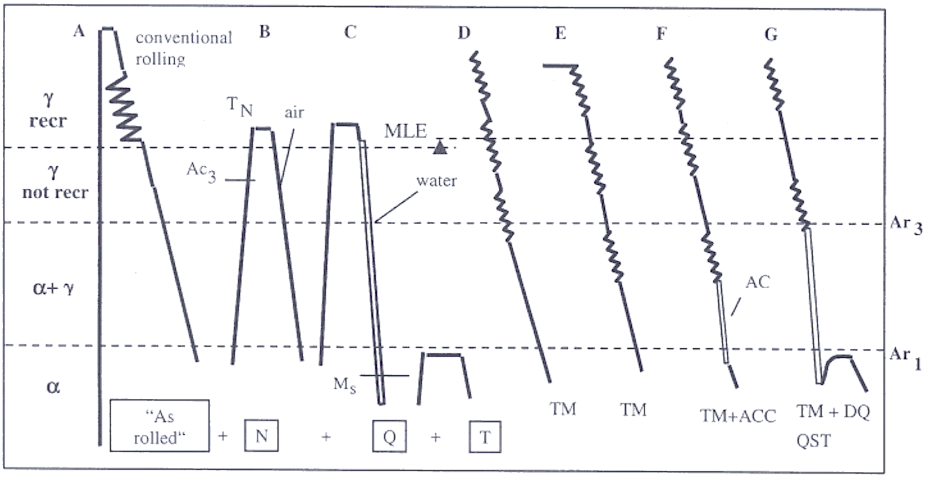

Fig. 5.1.2: Different types of heat treatment and rolling processes. Temperature on the vertical axis. γ recr denotes recrystallized austenite, γ not recr denotes non recrystallized austenite, α + γ the temperature range for austenite + ferrite and α the temperature region for ferrite and pearlite in conventional steels. MLE shows the increase in the temperature for recrystallization due to micro-alloying. T_N is the normalization temperature.

In the 1970s thermo-mechanical rolling process was developed and first applied for line pipe plates, but then quickly found its way into the fields of shipbuilding and the 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 at the same time a minimum alloying content resulting in best weldability.
Also here it is usual to add to the steel some micro-alloying elements such as niobium, vanadium or/and titanium in a very small amount 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 a temperature below the recrystallisation temperature (process D) and sometimes even in the temperature

range of coexisting austenite and ferrite/pearlite (process E). The process may be finished by an accelerated cooling especially for thicker plates (process F).
All these varieties of the TM-process produce a very fine-grained microstructure of ferrite and pearlite or – partly also bainite – as shown in Fig. 5.1.3, 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 thicknesses up to 80 mm and are already used in shipbuilding and offshore construction. For constructional steelwork even plates of 120 mm have been produced and applied successfully in particular in bridges.
Process G shows TM-rolling followed by direct quenching and self tempering. Here an outer layer of the material is quenched. The interior, being warmer, subsequently gives a tempering of the quenched material.

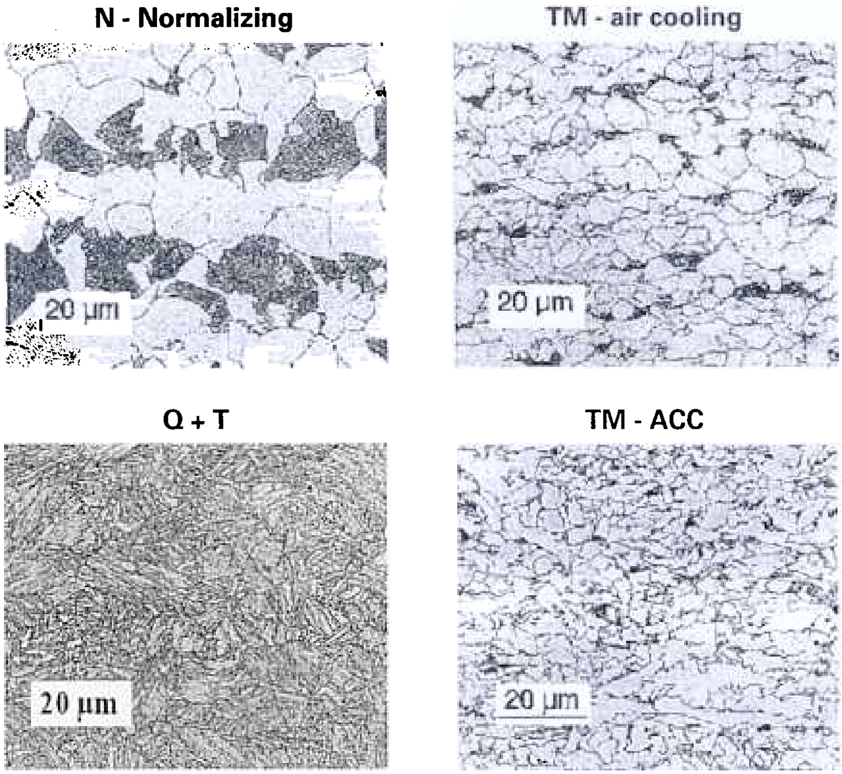

Fig. 5.1.3: Grain microstructure of QT and TM-steel compared to normalized steel

In the remainder of this article quenched and tempered steels will be referred to as QT and thermo-mechanically rolled steels as TM since Q and M (formal delivery conditions) are also quality designations for impact toughness.

5.1.3 Products and Properties

5.1.3.1 Standards

In November 2004 the new standard for hot-rolled steel products for usage in steel construction EN 10025 was published. This standard has six parts and defines the most common structural steel grades which were formerly treated in the independent standards EN 10113 and EN 10137. With reference to the higher strength grades, which are under discussion in this document, for each state of delivery explained in chapter 4.1.2, one part of EN 10025 (2004) is now reserved. However, as far as chemical and mechanical properties of the defined steel grades are concerned, these parts do not show big changes in comparison to the former standards EN 10113 and 10137. Regarding High-Performance Steels EN 10025 Part 4 (replacing EN 10113-3) describes TM steels with minimum yield stress of 420 and 460 MPa at the lowest product thickness. For each yield stress grade, two qualities exist with different guaranteed toughness levels measured by the Charpy-V test with the specimen in the longitudinal direction: an M-quality with 40 J at -20°C and an ML-quality with 27 J at -50°C.
QT steel grades are now standardised in EN 10025 Part 6 (replacing EN 10137-2) with yield stress grades from 460 MPa up to 960 MPa, whereas constructional steelwork in Europe today is limited to steel grades up to S690. Higher strength grades are still the domain of the construction equipment industry. Here, for each yield stress grade except S960 three different qualities exist Charpy-V tested in the longitudinal direction: a Q-quality with 30 J at -20°C, a QL-quality with 30 J at -40°C and a QL1-quality with 30 J at -60°C.
Table 5.1.1a, 1b and 2 summarises the mechanical properties of these steel grades according to the standard. Nevertheless, it must be recognised that products from actual production mostly exceed these minimum values by far.

Grade	Nominal thickness, mm					
	≤16	>16 ≤40	>40 ≤63	>63 ≤80	>80 ≤100	>100 ≤120
	Minimum yield strength R_{eH}, MPa					
S420M	420	400	390	380	370	365
S460M	460	440	430	410	400	385
	Tensile strength R_{m}, MPa					
S420M	520-680		500-660	480-650	470-630	460-620
S460M	540-720		530-710	510-690	500-680	490-660

Table 5.1.1a: Strength requirements for structural steels EN 10025-4, TM-steels

Grade	Nominal thickness t, mm $3 \leq t \leq 50$	$50 < t \leq 100$	$100 < t \leq 150$
	Minimum yield strength R_{eH}, MPa		
S460Q	460	440	400
S500Q	500	480	440
S550Q	550	530	490
S620Q	620	580	560
S690Q	690	650	630
S890Q	890	830	-
S960Q	960	-	-
Tensile strength R_m, MPa			
S460Q	550-720		500-670
S500Q	590-770		540-720
S550Q	640-820		590-770
S620Q	700-890		650-830
S690Q	770-940	760-930	710-900
S890Q	940-1100	880-1100	-
S960Q	980-1150	-	-

Table 5.1.1b: Strength requirements for structural steels EN 10025-6, QT-steels

Quality	Test temperature, °C -20	-40	-50	-60
M	40 J			
ML			27 J	
Q	30 J			
QL		30 J		
QL1				30 J
Energy requirements at the lowest test temperature are given for each quality. Transverse impact testing can be ordered as an option. For further details refer to the relevant standard.				

Table 5.1.2: Minimum energy values for impact tests on longitudinal specimens. TM and QT steels

5.1.3.2 Chemical Properties

The maximum alloying contents for high strength steels as given in the standards are often considered to give very conservative upper limits. Actual values for the products are usually much lower. Furthermore, it should be taken into account that not only the steel grade has an influence on the alloying content – in addition the chemical composition may vary with the thickness range. It is obvious that also differences between products of different producers are quite normal.

Table 5.1.3 gives examples of the chemical compositions of S460ML, S460QL and S690QL in comparison to the common European constructional steel S355J2. It can be seen that for grades up to S460 TM-rolled grades show a very "clean" chemical composition resulting in excellent weldability. But also the alloying concepts of the higher strength grade, in particular S690, allow for efficient fabrication processes, as described below.

	S355J2		S460ML		S460QL		S690QL	
	EN 10025 Part 2	typical analysis[a]	EN 10025 Part 4	typical analysis	EN 10025 Part 6	typical analysis	EN 10025 Part 6	typical analysis
C	≤0.22	0.17	≤0.16	0.08	≤0.20	0.15	≤0.20	0.16
Si	≤0.55	0.45	≤0.60	0.45	≤0.80	0.45	≤0.80	0.30
Mn	≤1.60	1.50	≤1.70	1.65	≤1.70	1.50	≤1.70	1.30
P	≤0.025	0.018	≤0.025	0.011	≤0.020	0.012	≤0.020	0.012
S	≤0.025	0.015	≤0.020	0.002	≤0.010	0.005	≤0.010	0.005
Nb	-	-	≤0.05	<0.04	≤0.06	0.017	≤0.06	<0.04
V	-	-	≤0.12	-	≤0.12	-	≤0.12	-
Ti	-	-	≤0.05	-	≤0.05	-	≤0.05	-
Mo	-	-	≤0.20	-	≤0.70	0.115	≤0.70	0.37
Ni	-	-	≤0.80	0.19	≤2.0	-	≤2.0	0.15
Cu	≤0.55	-	≤0.55	0.17	≤0.50	-	≤0.50	0.08
Cr	-	-	≤0.30	-	≤1.50	-	≤1.50	0.40
B	-	-	-	-	≤0.0050	-	≤0.0050	<0.003
CE	0.47	0.42	0.47	0.39	0.47	0.39	0.65	0.54
Pcm	-	0.26	-	0.19	-	0.19	-	0.29
CET	-	0.32	-	0.26	-	0.26	-	0.35

[a] Wide variation of the composition is possible due to a variety of possible production routes.
Carbon equivalents:
$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$
$Pcm = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$
$CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40$

Table 5.1.3: Chemical compositions of high-strength steel, 50 mm thick (weight-%). S355J2 is given for comparison. Excerpt from the standard requirements and examples of actual values.

5.1.3.3 Mechanical Properties

It has to be clearly stated that the values guaranteed by the standards are minimum values. The user can normally expect considerably better values, in particular for toughness. Fig. 5.1.4 shows as an example typical transition curves for the Charpy-V energy against the test temperature for an S460ML and an S690QL steel and compares them to a conventional steel, S355J2. It can be seen that these high-strength steels show significantly higher Charpy-V values at the testing temperature than given in the standard (27 J at -50°C and 30 J at -40°C respectively). Even at room temperature the toughness behaviour is better than for a conventional S355J2. These high toughness values also result in good welding properties as described below.

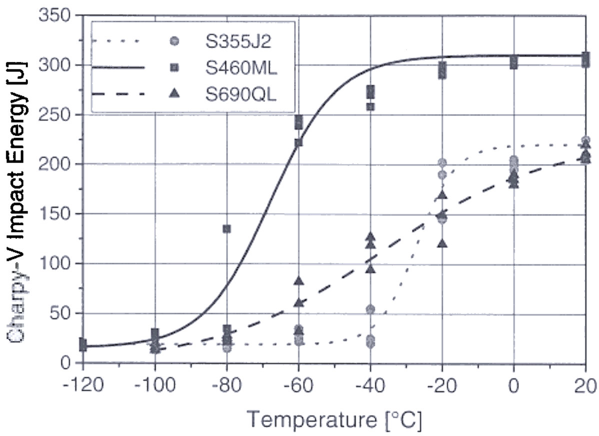

Fig. 5.1.4: Charpy V-temperature transition curves for S460ML and S690QL with S355J2 for comparison

5.1.4 Fabrication Properties

5.1.4.1 Welding

General recommendations for welding of TM and QT steels are given in EN 1011-2, Welding – Recommendations for welding of metallic materials – Part 2 Arc welding of ferritic steels.

Most steel producers give detailed information on welding on request. Such information may also be found on the respective Internet web sites of the steel producers. It is recommended to contact the steel producer for detailed information since the alloying concepts may differ between different producers.

The steels treated here have low contents of alloying elements and low carbon equivalents. They can be easily welded to all ordinary structural steels using any conventional arc welding method. This is especially true for the TM steels since an S460M steel has a lower carbon equivalent than an ordinary structural steel. The TM steels have a wider window for heat input and preheating than QT steels. Even for thicker plates of S460M preheating can be omitted and thus welding costs reduced.

The main points to avoid cold cracking are:

- Preheating the parent material when recommended. This is also most important for tack welding and the root pass.
- The joint surfaces should be perfectly clean and dry.
- Minimise the shrinkage stress by ensuring a good fit and a well planned sequence of weld runs.
- Use a filler material with low hydrogen content.

An example of preheating recommendations from one producer is given in Table 5.1.4.

Steel grade	Maximum combined plate thickness, mm										
	30	40	50	60	70	80	90	100	110	120	130
S460M, ML	Room temperature, RT							75°C			
S690Q, QL, QL1	RT		75°C				100°C		150°C		
Combined plate thickness is the sum of the thicknesses of the plates joined. Maximum hydrogen content of weld metal 5 mg/100 g. Heat input approximately 1.7 kJ/mm.											

Table 5.1.4: Example of preheating recommendations

The heat input determines the properties of the weld. Low heat input increases the maximum hardness and the risk for cold cracking, whereas high heat input decreases the toughness. Examples of recommendations are: For S420M, S460M up to 5.3 kJ/mm; for S690Q up to 3.5 kJ/mm, depending in both cases on the combined plate thickness. For thinner combined thicknesses, below 60 to 80 mm, the heat input must be reduced.

On the choice of filler material: Choose a filler material giving a hydrogen content ≤ 10 ml/100 g. For an S690 plate thicker than 20 mm, ≤ 5 ml/100g is recommended. Regarding S460M steels matching or overmatching material can be chosen, while for S690Q matching or undermatching is appropriate. For S690Q steel it is advisable to use an undermatching material for the root run. For fillet welds it is always advisable to select an undermatching filler material. The major benefits of selecting lower strength filler material for QT steel with yield strength > 500 MPa are: higher toughness of the weld metal, improved ductility of the joint, reduced sensitivity to cracking.

On stress relieving: EN 10025-1 has the following information. Stress relieving at more than 580°C for more than 1 h may lead to a deterioration of the mechanical properties of the steel grades as defined in parts 2 to 5. (Comment: this corresponds to the old standards EN 10025+A1, EN 10113-2, EN10113-3, EN 10155). For normalized or normalized rolled grades with minimum R_{eH} ≥ 460 MPa the maximum stress relief temperature should be 560°C. For the QT steel grades of EN 10025-6 (corresponding to EN 10137-2) the maximum stress relief temperature should be 30 K below the tempering temperature. For QT steels the purchaser is recommended to contact the steel producer. The maximum temperature is normally in the range 550°C to 580°C.

Our general practical experience is that post weld heat treatment is not necessary. The toughness and hardness of the weldment normally meet the requirements and is not substantially improved by stress relieving. It should only be carried out if a reduction of the residual stresses is needed for some special purpose or if specified in the design codes.

5.1.4.2 Flame Straightening

TM and QT steels can be flame straightened, but this requires more care than for conventional normalized or hot rolled steels. Gas heating and/or induction heating are recommended. The skill of the operator is essential. The temperature should be measured using thermocouples. Temperatures not exceeding 600°C for more than ten minutes do not affect the material properties detrimentally for QT steel of the type S690QL and S960QL [5.1]. For TM-material up to S460M it was shown that a superficial heating up to 950°C does not influence the mechanical properties significantly, whereas for more severe heating conditions up to the middle of the plates a maximum of 700°C should be observed [5.2]. The material manufacturer should be contacted if more detailed information is needed.

5.1.4.3 Cold Forming

General recommendations are found in ECSC IC 2 [5.3].

The material standards (EN 10025-4, -6) have a Note: "Cold forming in general leads to a reduction of the ductility. Furthermore it is necessary to draw attention to the risk of brittle fracture in connection with hot-dip zinc coating."

For TM steels EN 10025-4 has options regarding flangeability for material with a nominal thickness $t \leq 12$ mm and roll forming for material with $t \leq 8$ mm. For the steel grades S420 and S460 the minimum bend radius is 4 times t with the axis of the bend in the transverse direction and 5 times t in the longitudinal direction.

For QT steels EN 10025-6 has an option regarding flangeability for material with a nominal thickness $t \leq 16$ mm. For the S690 grade the minimum bend radius is 3.0 times t with the axis of the bend in the transverse direction and 4.0 times t in the longitudinal direction. Transverse and longitudinal refer to the rolling direction.

However, also in this respect the steels often have far better properties than specified in the standards. An example from one manufacturer is given in Table 5.1.5.

Grade	Thickness mm	Transverse R/t	Longitudinal R/t	Springback degrees
S420M, ML; S460M, ML		1.0	1.5	3-6
S690Q, QL, QL1	$t < 8$	1.5	2.0	6-10
	$8 \leq t < 20$	2.0	3.0	
	$t > 20$	3.0	4.0	
R denotes the punch radius and t the actual thickness				

Table 5.1.5: Example of bending recommendations from one manufacturer. They refer to shot blast and shop primed plate. As delivered plate may be bent somewhat narrower.

Most manufacturers give recommendations for bending and can be contacted for more detailed information such as estimates of the bending force needed.

5.1.4.4 Hot Forming

General recommendations are found in ECSC IC 2 [5.3].

According to EN 10025-4 TM steels shall not be hot formed. If deemed necessary the manufacturer shall be consulted. Often forming at a maximum temperature of 580°C for short times is allowed. QT steels can be hot formed. EN 10025-6 permits hot form-

ing up to the stress relief annealing temperature, normally in the range 550°C to 580°C. This agrees with the recommendations of the steel manufacturers.
In practice hot forming is rarely used due to the good cold formability of these steels.

5.1.4.5 Heat Treatment
TM and QT steels are not intended for heat treatment after delivery. The only exception is stress relief annealing as described above. TM steels obtain their properties during rolling, i.e. controlled deformation at precise temperatures. This cannot be repeated by heat treatment. QT steels are heat treated. However, the steel manufacturer normally has much more efficient quenching equipment than can be found elsewhere. The steel manufacturer adjusts the steel composition to match the properties of the quenching and tempering equipment to obtain the intended properties. Therefore a renewed quenching treatment may not restore the material properties and makes the inspection documents invalid. In rare cases, if heat treatment is deemed necessary the steel manufacturer must be consulted.

5.1.4.6 Zinc Coating
All of the steels in EN 10025 except those of part 5 have options for ordering grades suitable for hot-dip zinc coating. Reference is made to EN ISO 1461 and EN ISO 14713 or to special chemical requirements in the standards, see Table 5.1.6. These limits concern the thickness and appearance of the zinc layer.

Classes	Composition wt - %		
	Si	Si + 2.5 P	P
Class 1	≤ 0.030	≤ 0.090	-
Class 2[a]	≤ 0.35	-	-
Class 3	0.14 ≤ Si ≤ 0.25	-	≤ 0.035
[a] Class 2 applies only for special zinc alloys			

Table 5.1.6: Classes for the suitability for hot-dip zinc coating (ladle analysis)

For class 2 the maximum carbon equivalent CE shall be increased by 0.02, for class 3 by 0.01.
For the steels treated here class 2 is the most relevant one.
Galvanizing is a complex issue and only general advice will be given. For detailed information the steel manufacturer or companies performing galvanizing or their national associations should be consulted. The outcome for the highest strength steels is greatly influenced by details of the galvanizing process and the application. It is important that the galvanizing company is informed about the steel type.
The main problem for high strength steels is hydrogen cracking or zinc penetration into the grain boundaries of the parent material. Local stress concentrations or residual stresses from welding, gas cutting or cold forming will increase the risk. These problems may occur even for steels of the S355J2 type. Stress relieving and an abrasive water jet instead of flame cutting may reduce the problem.