MICROALLOYED STRUCTURAL PLATE ROLLING HEAT TREATMENT AND APPLICATIONS

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Abstract

Structural plates with a superior combination of mechanical properties and weldability are the result of a synergistic effect of microalloyed low carbon equivalent composition plus sophisticated thermo-mechanical control process variants or heat treatment during production in the plate mill. The paper considers both the production routes of such plate and the applications based on the beneficial type of microstructure and property profile.

Introduction

At the beginning of the 21st century sophisticated materials are used in the challenging field of civil engineering, construction and architecture. As an important type of material modern structural heavy plates are considered in this paper in terms of their development, production and use. The understanding of the role of microstructural features in relation to alloying elements, in particular microalloying elements, will be explored. In addition the exploitation of modern facilities in a plate mill, the tayloring of property combinations and the resulting possibilities for the construction industries are explained and illustrated with selected examples.

Production of Structural Plates

Requirements Made on the Plate Production Process

The following requirements are generally made on heavy plate: It must possess:

- The specified dimensions within narrow tolerances and with good flatness (thicknesses may range from 5 to 500mm and widths from around 1 to 5m);
- The yield and tensile strength required by the designers (yield strengths from around 235N/mm² to above 1100N/mm² can be specified);
- The toughness required by designers which may include low temperature;
- Ease the fabrication (e.g. deformability and weldability);
- If required, resistance to corrosion resulting, for example, from attack by the hydrogen contained in H_2S-bearing gases (sour gas), or a certain resistance to atmospheric corrosion (weathering resistance).

These properties are, in some cases, contradictory and have become achievable, in special combinations of alloying and processing technologies, only as a result of comprehensive development work and plant investments (1,2).

The technological status of present-day heavy plate production is described below. Slabs or ingots of appropriate size (continuous-cast strand thicknesses of up to 400mm and cast ingot thicknesses of up to 1000mm) are used, and a whole series of systematic process stages applied in a defined and repeatable manner, in order to produce heavy plate (Figure 1). These stages consist, essentially, of the heating of the slabs to rolling temperature, rolling and cooling, heat treatment if necessary, cutting to finished length, and ongoing testing and inspection operations.

The heavy plate producer must have qualified staff, efficient plant installations and suitable control and instrumentation systems for all process stages. Systematic procedures based on the most up-to-date know-how and considerable quantities of energy (heating gases, power for drive systems, etc.) must flow into the rolling mill as input; the output consist of, in addition to the plates, comprehensive process data required for the purpose of plate quality monitoring and evaluation, and test coupons for mechanical and technological testing by the acceptance inspection staff.

It only remains to state that more than 25,000 plates are produced from around 9,000 slabs or ingots each month at the plate rolling mill in Dillingen, for example, and that every plate is produced to order in accordance with the customer’s specification. The processes necessary for this purpose are examined in more detail below.

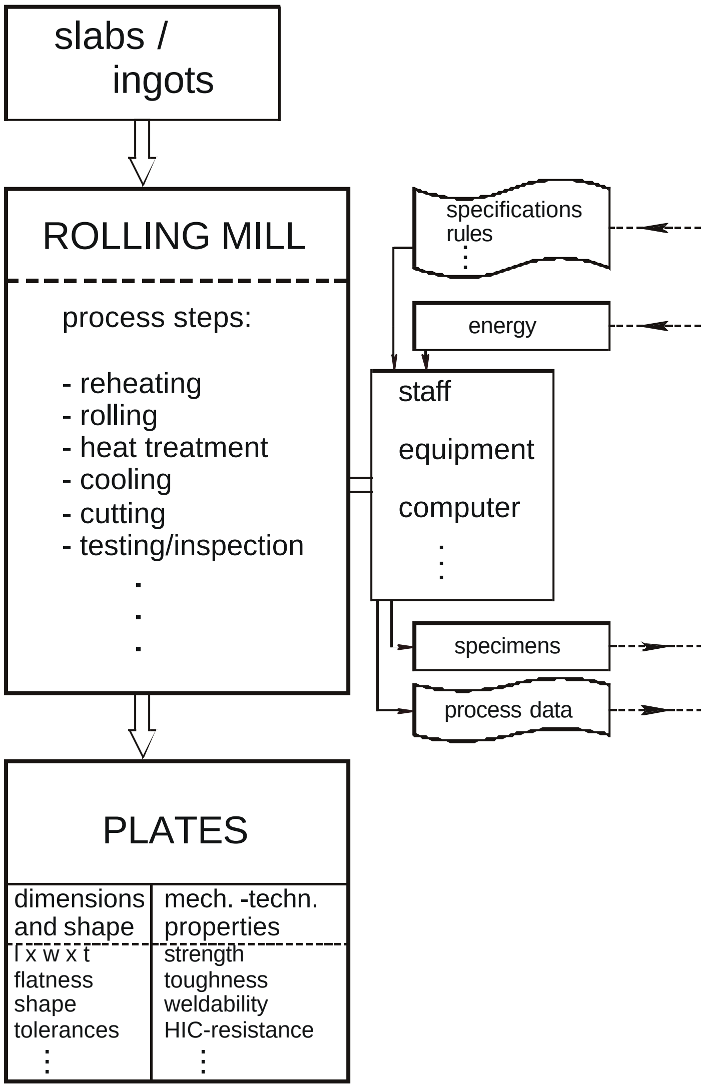

Figure 1: Input/output from a point of view of a heavy plate mill.

<u>The process Stages from a Metallurgical Viewpoint</u>

Starting from defined steel compositions, metallurgical mechanisms, which permit the achievement of the mechanical and technological properties required, must be activated in a range of different process steps. The metallurgically relevant stages, which contribute not only to the shaping (geometry) of the heavy plate but also to its mechanical and technological properties, by means of modification of its structure, are shown in schematic form in Figure 2.

Austenitization, including homogenization and the dissolution of micro-alloying elements, occurs during heating of the slab up to a defined temperature within the 1050 to 1200°C range. Depending on the temperature regime selected, a certain strengthening and grain refinement of the structure occurs during the rolling process which can be intensified as a result of the phase transformation and precipitation processes occurring during the subsequent cooling phase, the magnitude of such effects depending on the rate of cooling. The plates are generally hot-stacked in the lower cooling range in order to ensure removal of hydrogen by diffusion. Defined structure modifications can be accomplished via the application of heat-treatment stages of the most diverse types. The technologies involved are discussed in more detail in the sections below.

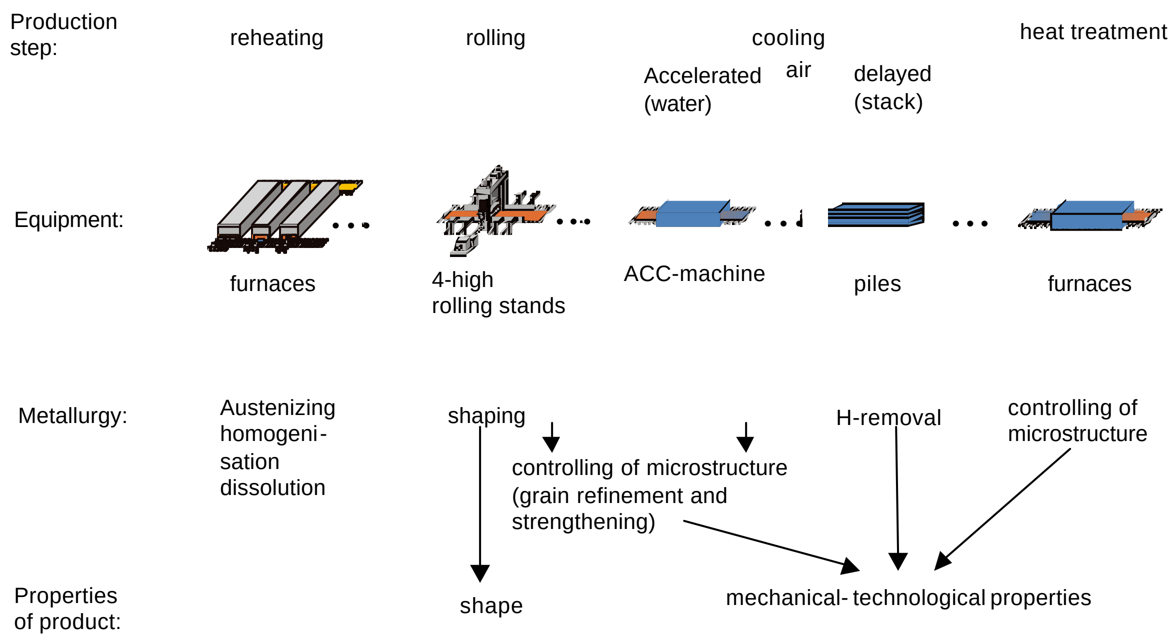

Figure 2: Process steps in the plate mill and their metallurgical objective.

The Hot-Zone of the Rolling Mill; Rolling as a Shaping Process

The typical installations in the "hot zone" within the layout of the Dillingen plate mill are shown in more detail in Figure 3. Geometrical conversion of the slabs arriving from the steelplant to plates is performed, after heating-up in pusher furnaces or bogie hearth furnaces, on two four-high rolling stands, which are among the world's most powerful and modern.

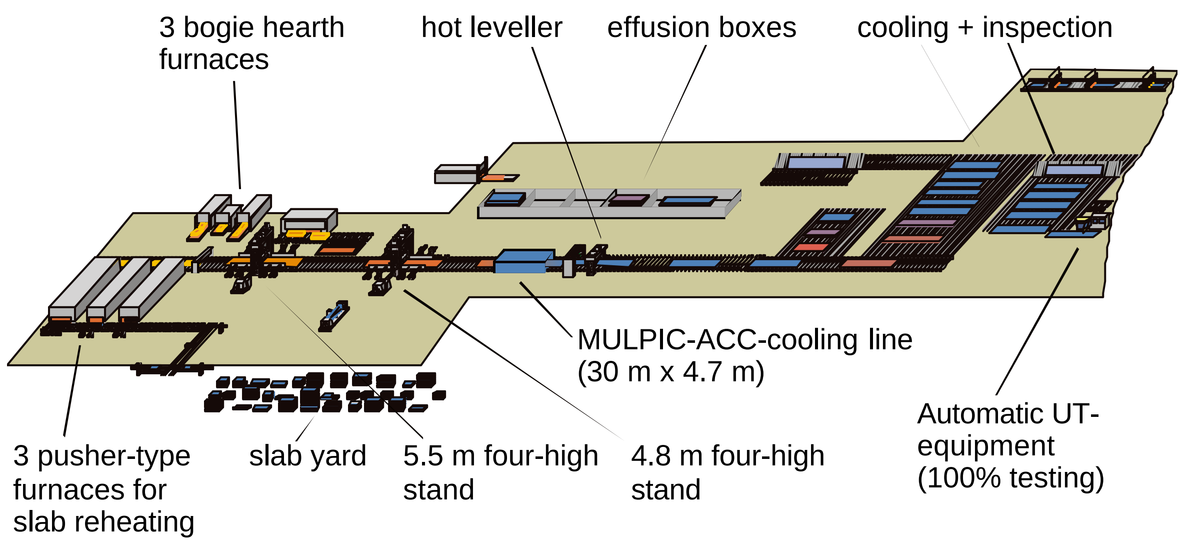

Figure 3: "Hot zone" within the layout of a heavy plate mill.

The starting point for the material flow is the slab storage area, which is connected directly to the steelplant's slab finishing zone. The adequate heating capacity provided by the installation of three pusher furnaces with seven rows for slab heating and three bogie hearth furnaces for ingots and special products should be mentioned. High-pressure scale removal is performed prior to rolling. The central element of the hot zone is made up of two four-high rolling stands with process-computer control, on which rolling is performed by the reversing pattern in widening and elongating passes.

Figure 4 shows plant-hardware details and, in particular, the large roll length of 5.5 and 4.8m, which permits the production of corresponding plate widths. The high-power drive systems (on the roughing stand, in particular, with its three-phase synchronous motor) make it possible to achieve metallurgically advantageous high per-pass reductions of up to 50mm. Special control and measuring facilities to ensure adherence to tight thickness tolerances include the AGC (**a**utomatic **g**auge **c**ontrol) and the thickness measurement system. WORB (**wo**rk **r**oll **b**ending) and BURB (**b**ack**u**p **r**oll **b**ending) are available for control of flatness, and a process model for drafting of the pass sequence.

Roll stand design:		features
1st	2nd	
5.5m 1985 (MDS) max. 108000kN max. 2 x 4500kNm AC synchr. max. 7m/s	4.8m 1971 (SECIM) max. 90000kN max. 2 x 3200kNm DC max. 6m/s	AGC WORB BURB at (2nd) computer process control ("PLATE")

Figure 4: Rolling stand design.

Particular process flexibility is achieved by the spacing of 105m between the two stands. Cooling can be accelerated with water cooling on the so-called MULPIC (**MUL**ti-**P**urpose **I**nterrupted **C**ooling) installation as an alternative to cooling of the rolled product in air. This 30m long installation can be deployed as an important "metallurgical tool", as is discussed in the next section. Plate flatness can be assured at the end of the hot zone using the hot-straightening machine, with the application of forces of up to 3000 t.

In the standard rolling process with no specific temperature requirements, also referred to as "normal rolling", rolling is used purely as a shaping process. The slab heated to high temperatures is converted to the plate geometry in a rolling phase and cooling is accomplished in air.

In special cases, and for thick plates in particular, it is important to completely exploit the potentials provided by the high-power stands. Maximum possible per-pass reductions during so-called HS (**H**igh **S**hape Factor) rolling improves the center quality of the rolled product. As Figure 5 illustrates, the importance of high per-pass reductions can be demonstrated by means of a corresponding experiment using prepared slabs. In the case of HS (**H**igh **S**hape Factor) rolling, the center of the rolled product is also deformed thoroughly resulting in good toughness properties and high tensile reduction in area values in the plate thickness direction.

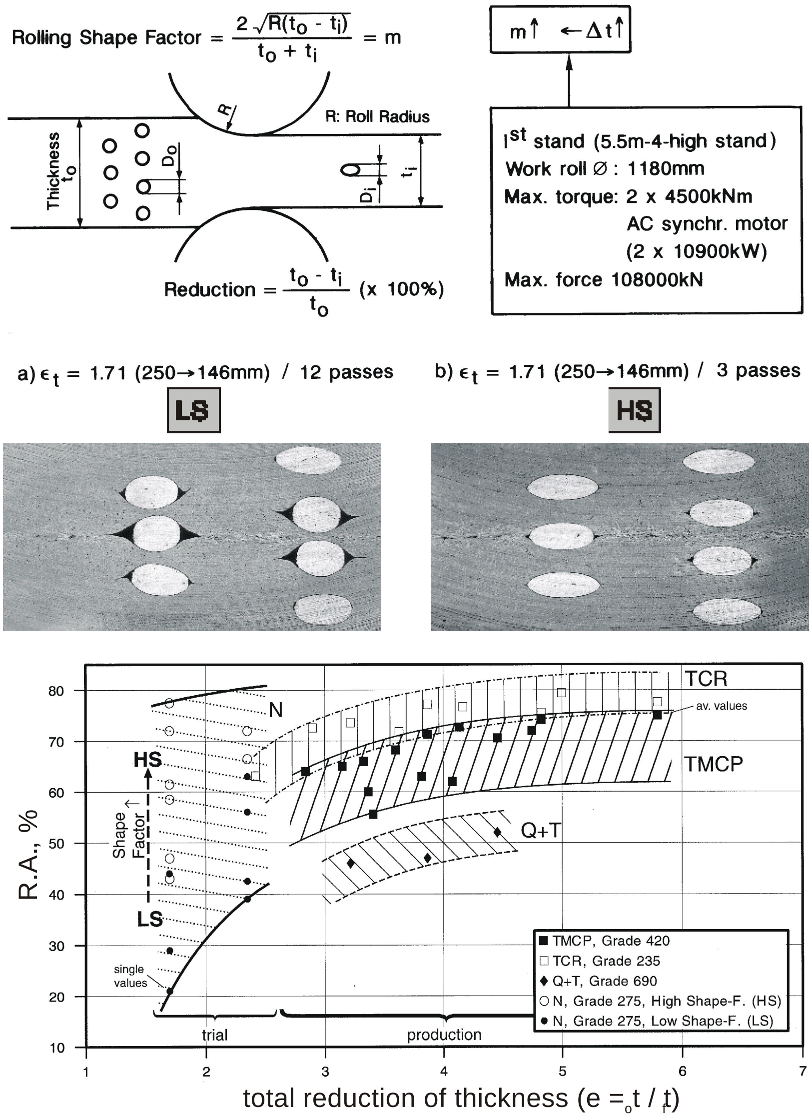

Figure 5:Influence of per-pass reduction on deformation and properties.

Process Variants for Control of Structure and Achievement of Delivery State

The rolling mill installations and metallurgical know-how mentioned above permit the use of tailor-made process variants depending on particular needs, or in other words, the plate property specifications (3-6).

The most important variants are compiled and compared in a time/temperature diagram in Figure 6.

Classical Processes: Rolling + Heat Treatment

The first group of process variants (A-C) is based on the "normal rolling" process (with no special temperature control of the rolling process):

Variant A. The heavy plate is delivered in state "U" (non-heat-treated, or "as rolled"), without any further modification of the structure by means of heat-treating.

A structure with a typical combination of properties can be achieved by means of heat treatment (combination of treatment at specified temperatures and cooling), viz.:

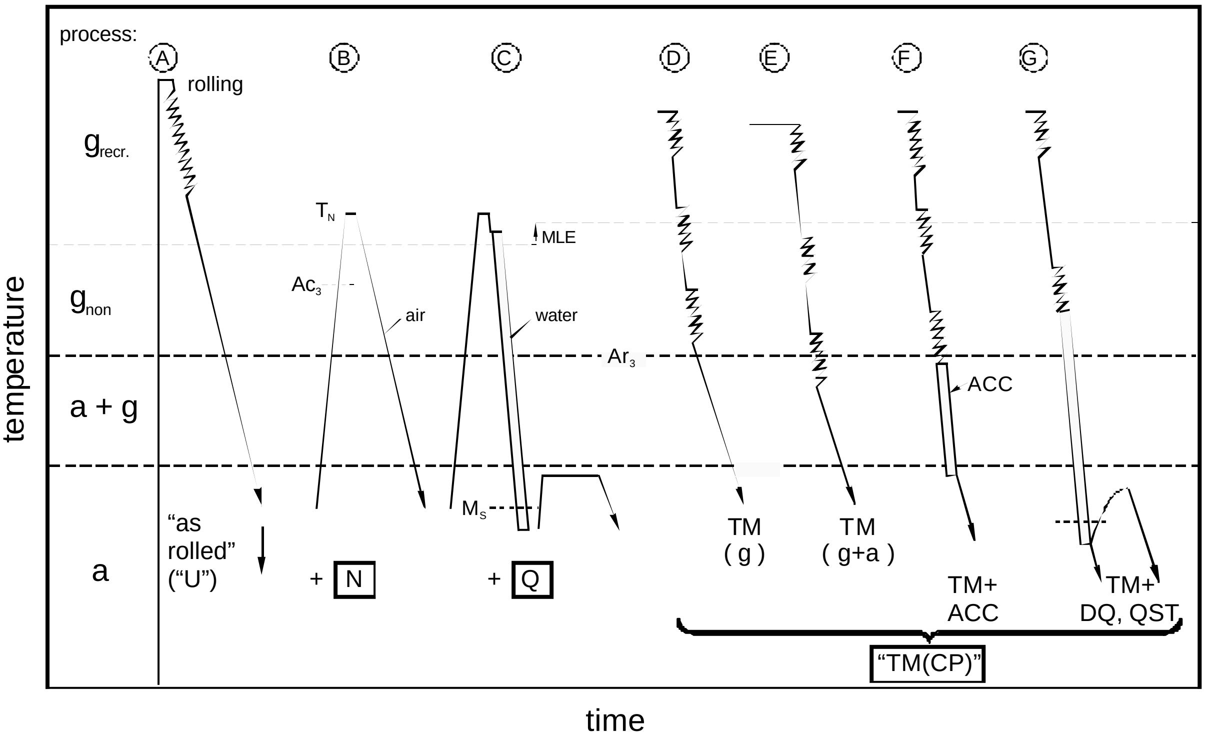

Figure 6: Time - temperature scheme for different process variants.

Variant B. Normal rolling + heat treatment "Austenitization (>Ac_3 , approx. 900°C) + cooling in air" = **N**ormalizing (N). This is performed in suitable furnaces either continuously (e.g. double walking beam furnace) or on a stationary basis (e.g. laterally chargeable furnace). The result is a structure consisting predominantly of polygonal ferrite and pearlite. The delivery state is abbreviated to "N". Higher yield strengths and tensile strengths can be achieved for normalized steels only by means of higher alloying element contents; there are therefore limits on the possible property combinations achievable in the heavy plate using this process. An equivalent state can be achieved by means of normalizing rolling, i.e., rolling with the final deformation in the N-temperature range, which is therefore also designated as "N". Plates in state "N" are used, among other things, for boiler- and pressure-vessel making, in particular.

Variant C. Normal rolling + heat treatment "Austenitization (>Ac_3) + water quenching" = **Q**uenching (Q) or hardening. This process is performed in a combination of a roller hearth furnace and a roller quench, or on a stationary basis in quenching boxes. Due to the extremely high rate of plate cooling, the result is a hard structure consisting predominantly of martensite and bainite. The toughness of the structure is increased by modifying the originally hard and brittle martensite zones by means of subsequent tempering (in a further roller hearth furnace, for example, at temperatures of around Ac_1 –100°C, i.e., approx. 600°C). A heat-treated structure results in a combination of a still relatively high hardness or yield strength and tensile strength with an improved toughness. Quenched and tempered steels are used in particular where requirements for strength or/and resistance to wear are especially high.

<u>Thermo-Mechanical Treatment Processes</u>

The demands for high strength in large diameter linepipes (low wall thicknesses and high transmission pressures in the case of natural gas), combined with high toughness at low temperature and good weldability, have resulted in the development of "**T**hermo-**M**echanical rolling", the extremely diverse forms of which can nowadays be grouped together under the umbrella term "TM" (or TMCP = **T**hermo-**M**echanical **C**ontrol **P**rocess).

The essential difference vis-à-vis the classical processes discussed up to now can be found in the fact that rolling is used not only as a shaping process but also for the achievement of a specific combination of properties. TM rolling can therefore be defined as a process which aims at achieving a structure with a fine effective grain size permitting a favorable combination of service properties, is tailored to the steel composition, and is composed of a sequence of the following steps controlled in terms of time and temperature:

- Slab reheating: with a defined drop out temperature;
- Rolling: on the basis of a specified pass sequence with finish rolling in the non-recrystallized austenite or (α+γ) two phase zone;
- Cooling: either in air or in the stack, or in accelerated form in the cooling line, down to a defined final cooling temperature;
- Possibly, additional heat treatment (tempering).

The essential benefits of TM rolling are based on the effects of microalloying. The key element is niobium (Nb) as it:

- Retards or suppresses recrystallization of the austenite (formation of new grains between the individual rolling passes). The deformation effect of a large number of passes at temperatures of around <850°C is accumulative, permitting the formation of very fine grains during transformation.
- Forms carbonitride precipitates which block dislocation movement in the atomic lattice and thus results in increases in yield strength and tensile strength (precipitation hardening).
- Retards, if in solid solution, the γ to α transformation.

These effects of niobium can be exploited during processing making it possible to reduce alloying element contents and carbon content while maintaining high toughness values and good weldability at identical or higher yield strength and tensile strength values. The alloying content of niobium is chosen with regard to the process route and property requirement applied process (Figure 7) (7).

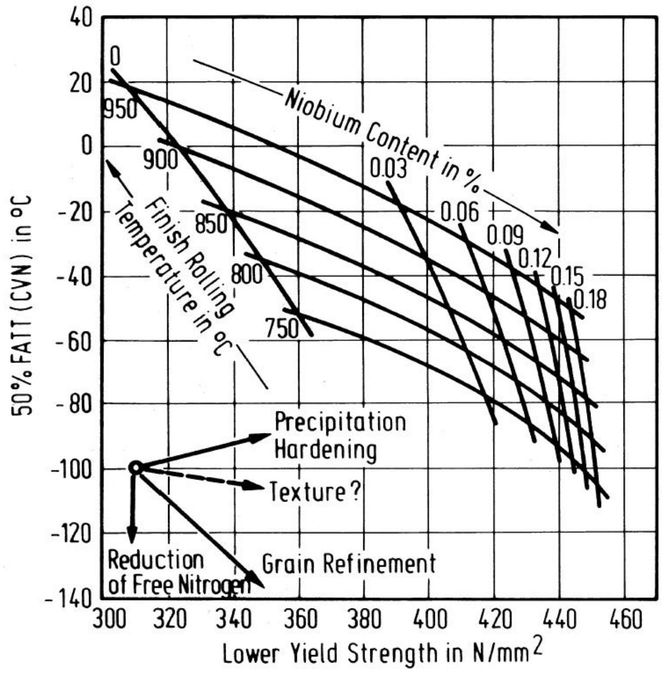

Figure 7: Mechanical properties of a 0.08 % C - 1.50 % Mn steel as a function of niobium content and rolling conditions (7).

The exploitation of strengthening mechanisms to best achieve the specified properties by means of microstructure control can be accomplished using an appropriate range of equipment in the rolling mill. As Figure 6 shows, it is therefore possible to differentiate between a number of basic TM variants, the delivery designation being abbreviated, in accordance with the relevant standard, to "M".

Variants D and E. For process variants D and E, the mechanisms mentioned are controlled using a number of rolling phases which differ from one another, for example, in terms of temperature levels and degrees of deformation. The final rolling temperature may still be within the non-recrystallizing γ range (austenite) (D) or even lower in the $\gamma+\alpha$ two phase region (E). This makes it possible to achieve strength- and yield strength enhancement by low temperature deformation. Cooling of the plate is in air in both cases.

Variants F and G. In the case of variants F and G, rolling is performed in a manner similar to that for D or E but with the addition of accelerated cooling in order to achieve the required properties at increased plate thickness or to increase yield strength, tensile strength, toughness and suitability for sour-gas service. The plate is subjected after rolling to accelerated cooling with water at a defined rate of cooling in the MULPIC installation. These processes can be classified on the basis of the cooling route selected, as shown in Figure 8. In the case of ACC (accelerated cooling), cooling as shown in Figure 8a is used and results in cooling with the “ideal” cooling rate. In case of Variant G, the fastest possible cooling of the surface, similar to conventional quenching (Variant C), is applied. In the DQ (**D**irect **Q**uenching) case, the center of the plate is also cooled to below the martensite-start temperature by means of continuation of cooling (Figure 8b). In the QST (**Q** + **S**elf **T**empering] case, the center heat still present is exploited after an extremely short cooling time and self-tempering is achieved (Figure 8c).

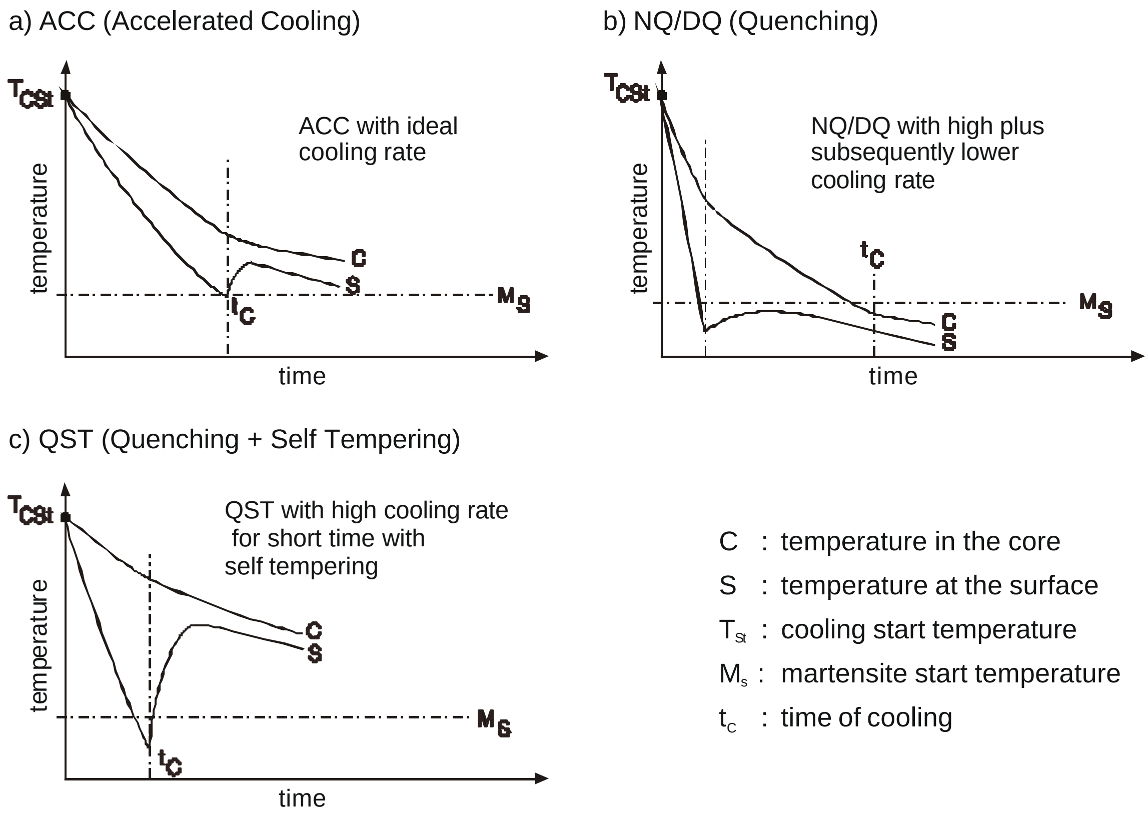

Figure 8: Design of cooling process - aspects and variants.

The differing extents to which strengthening mechanisms are initiated by means of TM rolling and accelerated cooling up to and including direct quenching for a given steel composition compared to the normalized state are shown in Figure 9. The gains in yield strength and tensile strength compared to the N state achievable by means of TM + ACC or DQ are shown for a given plate thickness (25mm) for a micro-alloyed steel composition with a low carbon equivalent.

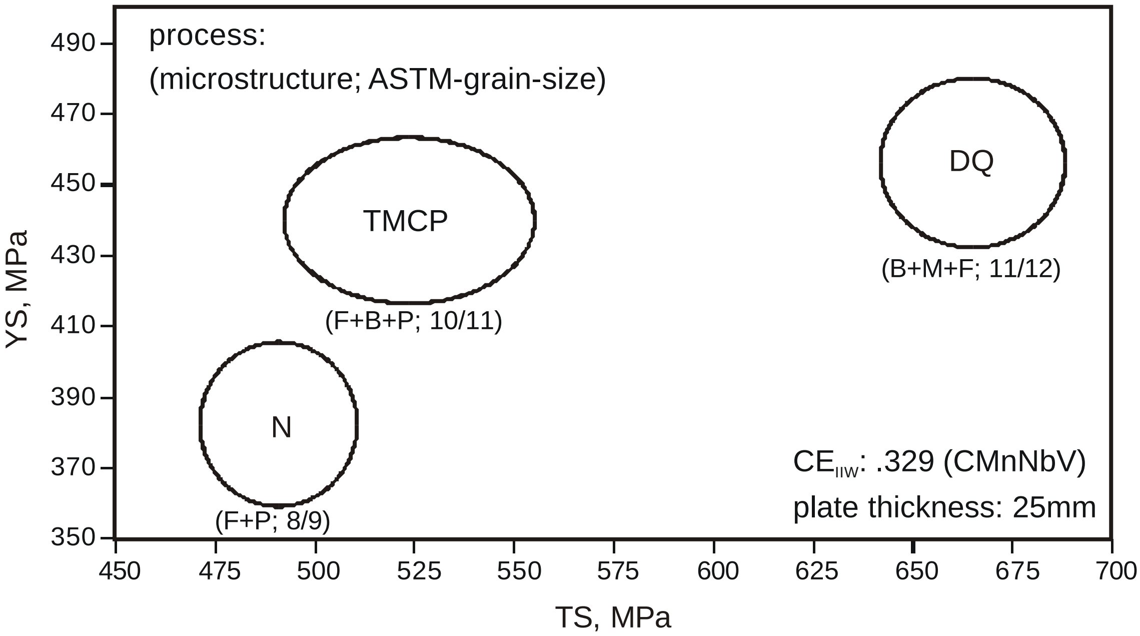

Figure 9: Comparison of strength properties for different processes.

All the important process parameters and process controls necessary for the technological achievement of the TMCP process are shown in Figure 10. The essential stages of the TM process can be traced in the plant layout of the hot zone of the Dillingen rolling mill (Figure 3):

- Slab heating in the pusher furnace and bogie hearth furnace;
- Rolling on the reversing four-high rolling stands;
- Cooling on the MULPIC cooling line.

Defined and repeatable slab reheating presupposes controlled operation of the furnace on the basis of mathematical models based on the physics of heating. The technical control and performance of the reversing four-high rolling stands are an essential part of the deformation process. High rolling forces are necessary, particularly for TM pass sequences with low final rolling temperatures. Repeatability presupposes rapid and precise process regulation based on the most accurate possible measurement of product temperature and thickness and of rolling force. The use of a tandem-rolling pattern, with a number of slabs in the stands simultaneously, is desirable for achievement of cost-efficient throughputs. Cooling of the finish-rolled plate is performed in air, on the roller table or cooling bed, in the stack or, if necessary, using accelerated cooling in the cooling line.

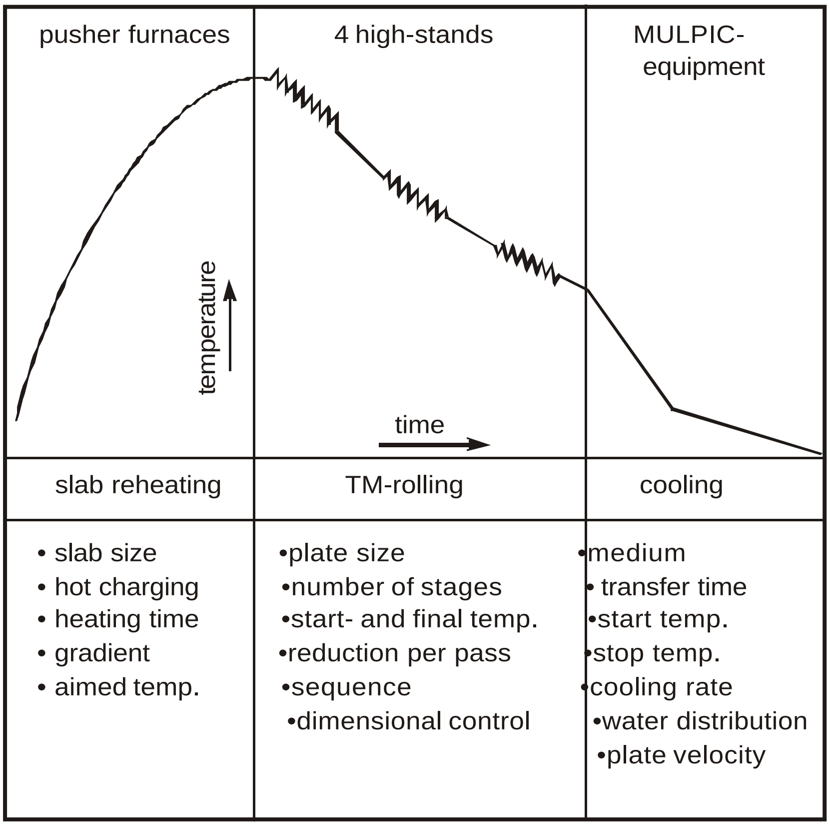

Figure 10: Process parameters of TMCP.

Since accelerated cooling of the most diverse range of plate thicknesses (from around 12 to 120mm) and direct quenching were to be achieved in a single installation in the Dillingen cooling line, the emphasis in selection of the cooling system was on a wide range of cooling intensities. The particular form of the MULPIC cooling system selected, with a high-pressure section, is characterized by: water-cushion cooling of the plates using a series of upper and lower units fitted above and in the roller table, high variability of water flow, from 70 to 2500l/m² per min, and thus a cooling intensity which can be varied within broad limits. The control diagram for this installation is explained in Figure 11. Computer-assisted process control of the cooling process is accomplished by means of two coupled systems; on the one hand via the conveying control system for plate travel speed on the roller tables, either reversing in the installation or passing through continuously, and on the other hand via the water control system for the achievement of the homogeneous application of water.

The TM treatment variants discussed above have now been in use for more than fifteen years for the production of heavy plate in large tonnages for large diameter linepipe for conveyance of oil and gas transmission and, for a number of years now, for shipbuilding and structural engineering applications (bridges and offshore drilling platforms).

Common to all the process routes examined above, and particularly true of the more recent routes, is the role of process control and quality assurance in the achievement of all the specified requirements. In practice, a tolerance range ("window") of property figures is permitted, but must be achieved within certain statistical limits, i.e., repeatably, which in all cases demands good knowledge of the underlying metallurgical interrelationships and adjustment of all process parameters within defined standard deviations, both during steelmaking, i.e., adherence to the target composition, and also during the TM rolling process, including cooling, and on-line monitoring and approval systems.

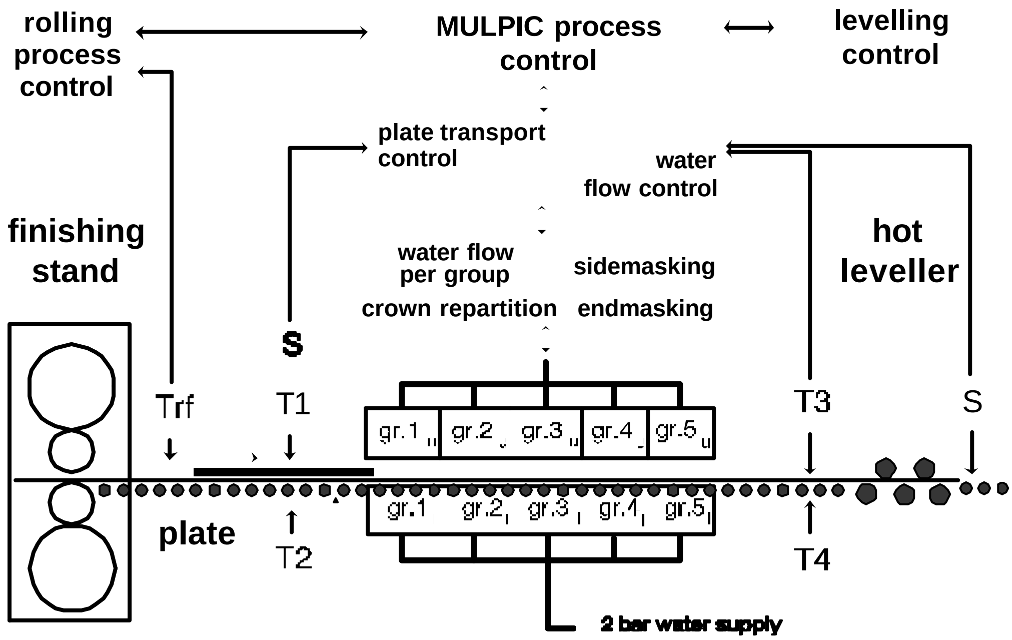

Figure 11: Control diagram of the MULPIC cooling device.

<u>Further Process Stages up to the Completed Plate</u>

Once the required properties in the plate have been achieved by means of controlled-temperature rolling processes and/or heat-treatment stages, there are still a number of important process stages or steps until the finished plate is achieved, as is shown in Figure 12.

A) Rolling (shaping, where required TM-effect)

B) Heat treatment

C) Additional production steps in the rolling mill:
- Hot and cold levelling (flatness)
- H - effusion treatment
- Cutting
  - Shearing
  - Flame cutting
- Plate testing
  - US-testing
  - Surface inspection
  - Dimensional inspection
- Sampling for destructive testing
- Shot blasting (+ coating)
- Shipping / Loading / Dispatch on truck, railway, vessel

Figure 12: Production steps in the heavy plate mill.

Extensive conveying systems such as roller tables, magnetic cranes and special transporters are available for handling of the mother plates or individual heavy plates in the plant. Straightening of the hot or the cold plate may be necessary, depending on flatness specifications. Stacking of the plates has a dual role, that of hydrogen removal and that of buffering the upstream finishing zone. It must be possible to trace the origin and specification of the mother plates and individual heavy plates by means of unique identification numbers (reference numbers). The plates are stamped and paint-marked for this purpose. Conversion of the mother plate to an individual plate is accomplished by means of trimming the edge scrap and cutting the mother plate in the transverse and/or longitudinal direction, either on the shear line or, in the case of thick plates and high-alloyed steels, by means of thermal cutting. Non-destructive testing procedures, such as on-line ultrasonic testing, for example, or surface and dimensional checks, and the taking of coupons for destructive materials testing, are performed for the purposes of quality monitoring. If specified, the plate can be shot blasted and protected with primer. The finished products are shipped to the customer from the plant by road-truck, rail or ship.

Process Development as the Basis for the Achievement of Modern Specifications

The production process for heavy plate may include many diverse combinations of process stages. A broad potential for innovation derives from their optimization. Systematic and balanced harmonization of customers' wishes and the producers' capabilities can be achieved by means of close cooperation. The requirements placed on the heavy plate producers by customers with respect to product properties and dimensions, in particular, and also fabrication and service characteristics, can only be achieved if the foundations for new process variants are laid in a carefully tailored manner by means of systematic investment and methodical development activities.

Applications of Structural Plates

Fields of Use

There are traditionally three important applications for heavy plates in civil engineering: heavy steel structures of welded construction (for example multistorey buildings, ship-building halls or power plant buildings), bridges with spans between 4 and 1000m and offshore platforms for oil and gas production and processing. The microalloyed high strength structural plates offer to technical designers a nearly unlimited range of dimensions, strength and toughness levels. Due to their optimised properties heavy plates provide for the possibility of very economical and durable constructions.

User-Oriented Development of Heavy Plates

At present heavy plates are widely used in constructional steelwork. Over many years the steel grades between S235 and S355 have been very popular. The development of heavy plates for steel structures during the past several decades firstly aimed at increasing the strength level while keeping an acceptable weldability. Thus, the volume of steel used in a construction could be reduced - a decisive cost factor at that time. At the beginning of the 1970s, the high-strength steels S460 and S690 were developed, but unfortunately the welding of these plates was relatively expensive.

Fabrication and manufacturing costs savings gained more and more importance during the 1980s and led to the development of the modern generation of microalloyed thermomechanically (TM or TMCP) rolled heavy plates (1). TM-rolled heavy plates in steel grades S355, S420 and S460, which have been available since the end of the 80s, offer not only a high strength but also an excellent weldability. Thus, the possibility of designing even more economical steel constructions was established. Table I compares the steel composition of a steel grade S460 (yield strength ≥ 460 N/mm²) for the delivery condition normalized (S460 NL) and TM-rolled (S460 ML). The normalized process route makes use of a relatively high carbon content and vanadium precipitation to get the required strength level. In comparison, the TM-rolled steel utilizes the effect of niobium, as described above, in combination with noticeable lower vanadium and carbon contents and consequently lower carbon equivalent.

The recent heavy plates for offshore applications were derived from microalloyed fine-grained structural plates and standard grades such as the normalised S355N. They are designed to give a favourable toughness in the heat-affected zone after welding. Since the end of the 80s TMCP-heavy plates of the yield levels 355, 420, 450 and 500 have been developed for constructional steelwork (8,9). These grades are characterised by excellent toughness levels after welding even with the high strength properties.

Table I Alloying of normalized and TMCP steels for grade S460 (50 mm)

	S 460 NL		**S 460 ML**	
	acc. EN 10113-2	typ. analysis	acc. EN 10113-3	typ. Analysis
C	< 0.20	0.17	< 0.16	0.09
Si	< 0.60	0.45	< 0.60	0.30
Mn	1.00-1.70	1.65	< 1.70	1.50
P	< 0.030	0.015	< 0.030	0.011
S	< 0.025	0.010	< 0.025	0.005
Nb	< 0.05	-	< 0.05	< 0.04
V	< 0.20	0.17	< 0.12	< 0.05
Mo	< 0.10	-	< 0.20	-
Ni	< 0.80	0.29	< 0.45	0.25
CE		0.50		0.37
p_{cm}		0.29		0.19
CET		0.34		0.25

carbon equivalents: $CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni+Cu)/15$

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

$CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40$

Building Construction

As far as building construction is concerned, two different fields of application may be distinguished; on the one hand the simple, standardised multistorey and high rise buildings and on the other hand heavy welded constructions for industrial halls, power plant and specially tall multistorey buildings. Regarding the standardised constructions, which have the big-gest share of total steel consumption in the construction market, heavy plates are only used for head plates or stiffeners for framework constructions predominantly composed of rolled beams. This is mainly a market for steel grades S235 and S275.

In cases in which high loads or large spans have to be designed, columns, piles and girders are normally welded and made from heavy plates. This design and construction method shows an economical advantage at sizes greater than a girder height of about 600 mm because the cross sections of the supporting structure can be adapted individually to the constructional task by using only a minimum of steel. The steel grade S355 is predominantly applied for these applications, but sometimes even heavy plates of the higher steel grade S460 are used.

The following are examples of the typical application range of heavy plates:

- Power plant buildings, e.g. the thermal power station Schwarze Pumpe, Germany, (Figure 13) with an overall height of 161 m. The columns and beams were mainly fabricated with TM-rolled heavy plates S355M/ML and the standard structural steel S255J2G3 mod. in plate thicknesses up to 65 mm. Additionally, S690QL grade in some high tension loaded areas was used.

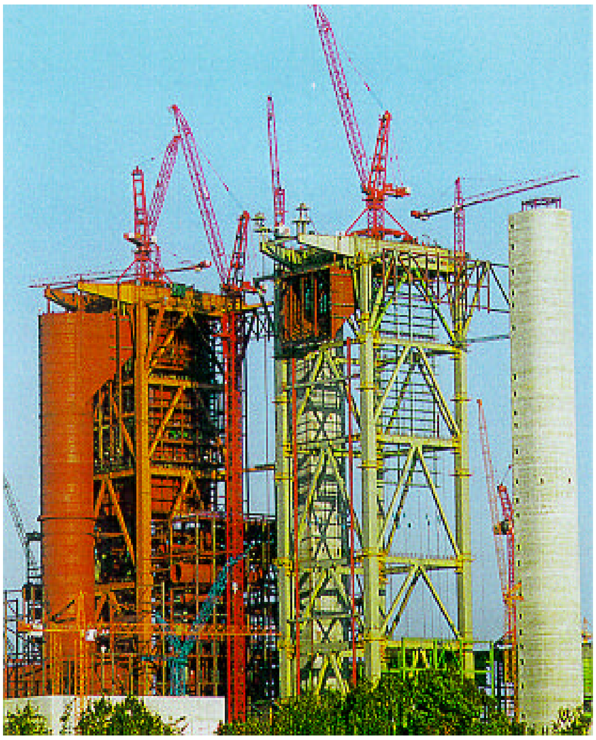

Figure 13: Thermal power station Schwarze Pumpe, Germany.

- Commerzbank Tower, Frankfurt, Germany (Figure 14)
  Due to the very high requirements of architects regarding the aesthetics of multistorey buildings, heavy steel skeleton constructions have been more and more used during the past 10 years. A typical example for this is the Commerzbank Tower in Frankfurt with a height of more than 298m (10). Its steel framed structure contains about 18000 t of heavy plates. S355M steel was used for plate thicknesses exceeding 30 mm, whereas in highly loaded girders and columns S460M. Thus, fabrication costs were reduced by the selection of these heavy plates.

- Sony Center Berlin, Building F, Germany
  Also in this example the architectural requirements made it necessary to use high-strength heavy plates. The supporting structure consists of 3 heavy columns on which 2 welded truss girders made of heavy plates form the load bearing structure. On the latter the individual stories are supported. The truss girders were made of plates with thicknesses up to 100mm of grades S460M/ML and S690QL1 (11).

- ICE- High-speed train station Frankfurt-Airport, Germany
  The 700 m-long and 50 m-broad reception hall of the high ICE-station near the Frankfurt airport rests on heavy welded columns. More than 18000 t of steel grades S355M/ML and nearly 2000 t of S355K2G3 were used for this building. Each upper supporting framework

has a weight of about 320t and is supported by columns with an individual carrying force of 7500 t.

Figure 14: Commerzbank Tower, Frankfurt, Germany.

Bridges

In bridge construction during the last several years more and more heavy plates have been applied, in particular due to progress in the construction of composite bridges (steel supporting structure with a concrete deck) (12). For this style of construction, bridges are usually medium span with sizes between 30 and 150 m. These structures can exploit the whole range of plate dimensions and steel grades. Very thick plates (girders with a thickness of up to 150 mm) are as well used as very wide plates (width up to 4300 mm and, in special cases, also more than 5000 mm), and long plates for segment lengths between 18 and 36 m for steel grades up to S690QL1 (13). These ranges in plate dimensions allow very cost-saving bridge construction.

Bridges with Very Small Spans. Between 3 and 6 m can be built using a single heavy plate (14). Plate thicknesses up to 250 mm may be reached depending to the loading and the deflexion criteria used. Typical plate bridges are La Moyaz and Creux de Mas in Switzerland. These plate bridges consist of heavy plates of steel grade S275NL lying side by side. The dimensions used in these plate bridges are: thicknesses between 160 mm and 220 mm, widths of about 2300 mm and a length of about 4400 mm. The main advantage of this bridge type is the small traffic interruption period during erection of the bridge. So, the whole process of erecting the bridge from pulling down the old bridge structure up to the passage of the first traffic does not take more than 8 hours.

Due to construction technique, bridges with big spans (more than 150 m) belong to the field of pure steel structures. Structures made of welded heavy plates are almost generally applied to such types of bridges.

Mainly heavy plates of steel grade S355 are used in European bridge building. However, high strength plates of S420 and S460 are more and more employed for large-span bridges. Sometimes even the higher-strength steel grade S690, e.g. in the water-quenched and tempered condition, is used. Normally the plate thicknesses are less than 50 mm, but exceptionally even plates of thicknesses up to 150 mm can be found in the load bearing sections.

Typical examples for modern bridgebuilding are given below:

- ICE-High speed railroad bridge Nantenbachtal, Germany
  The double-track composite bridge (15, 16) has an overall length of 695 m and a maximum overall height (at the posts) of 15.5 m (Figure 15). The main span is 208 m. This three-span, concrete-haunched composite building consists of an upper concrete deck plate and a concrete compression plate in the region of negative bending moments above the abutments (double composite). Steel grade S355J2G3 mod. is used in plate thicknesses up to 65 mm.

Figure 15: Bridgebuilding with heavy plates, Nantenbachtal-bridge, Germany.

- TGV-Méditerranée, France
  Among the 23 bridge constructions 15 were established as composite bridges with twin girders. The most important composite bridges are the bridge of Cavaillon (5200 t), the bridge of Orgon (3600 t) and the bridge Cheval blanc (3500 t). In addition, 5 smaller bridges and three big truss arched bridges were built in steel: Viaduc de Donzère, Viaducs de Mondragon and Mornas. Besides the classical steel grade S355K2G3 (plate thickness up to 30 mm) also heavy plates of the steel grades S355N and S355NL (plate thicknesses more than 80 mm) were used, some in the form of LP-plates (**L**ongitudinally **p**rofiled plates).

- Erasmus-bridge Rotterdam, The Netherlands

The Erasmus-bridge (17) connects the inner city of Rotterdam with the North bank of the Nieuwe Maas, Kop Van Zuid, where a new quarter has been established on a former harbour area (Figure 16). The steel bridge has an overall length of 499 m with a 410 m-long cable-stayed bridge composed of a 139 m-tall pylon and a 89 m-long hinged bridge. In total, 6000 t of heavy plates of grades S355M (thickness less than 100 mm, 4200 t), S460ML (thickness less than 80mm, 2000t) and S460QL (thickness less than 125) were used for this bridge.

Figure 16: Bridgebuilding with heavy plates, Erasmus-bridge, NL.

- Øresund-bridge, Danmark-Sweden
  The Øresund fixed link consists of a 7500 m-long framework composite bridge, a 4000 m-long artificial island and a 3500 m-long tunnel. The approach bridges and the cable-stayed main bridge were built as a truss bridge with a upper concrete deck and a lower steel deck (railroad deck). Heavy plates of the steel grade S460M/ML in thicknesses up to 80 mm (60000 t) were used for the shore spans, whereas the main bridge was constructed of S420M/ML in thicknesses up to 50 mm (16000 t).

- Normandy-bridge, France
  In 1995 the Normandy-bridge (18) was opened to traffic. At that time it was the biggest cable-stayed bridge in the world. 624 m of the total length of the main span (856 m) were constructed of heavy plates for weight reasons. The aerodynamically optimised cross section has been designed and built using plates in steel grades S355K2G3, S355N and S420M in thicknesses up to 30 mm (single pieces up to 125 mm).

Offshore Construction

In the 60s and 70s the construction of offshore platforms for oil and gas production in the North Sea required heavy plate properties significantly exceeding the requirements of conventional structural steels. Due to the high requirements regarding the safety and reliability of the platforms under even very extreme external conditions (low temperature, severe storms, high waves, corrosion by sea water) as well as the necessity of a partial assembling on site at sea, heavy plates with especially high ductility, high resistance against crack growth and good fabrication properties had to be developed. These steels utilise microalloyed fine-grained steels specially developed to meet offshore specifications.

The supporting framework of platforms standing on the ocean floor usually consists of a framework made of relatively thick-walled tubular sections. In order to produce these sections economically, the heavy plates have to be as wide as possible. This allows the number of tubular segments necessary to form the welded framework structure to be greatly reduced. Typical plate widths for such structures are between 3500 and 4500 mm with thicknesses between 20 and 90 mm. Today, heavy plates of steel grade S355-Offshore are used as standard. These plates can be delivered in either a normalised or a TM/TMCP-rolled condition with a thickness up to 250 mm and 120 mm respectively. In particular, the TM-rolled heavy plates show favorable toughness properties after welding and can be processed in a very cost-saving manner.

Recent platform construction is characterised by the necessity of a higher overall height due to deeper sea levels or the development of floating platforms. When using the classical S355-Offshore steel grade in these constructions, the necessity of large load-carrying cross sections considerably increases the total weight of the structure. Therefore, higher-strength heavy plates of the steel grade S420-Offshore have won recognition in platform applications. These plates are delivered in thicknesses up to 120 mm in a TM/TMCP-rolled condition. Plates with greater thicknesses are normally used in the quenched and tempered condition.

The following descriptions provide typical examples of modern offshore platforms:

- Ekofisk IIa (Figure 17)
  The Ekofisk-field, a very old oil and gas field near the Norwegian coast, had to be reconceived because of the lowering of the central storage tank. Therefore, two new platforms were built. About 45.000 t of plates predominately of the steel grade S420M-Offshore were used for these two platforms. The six-legged platform 2/4X weighs 7900 t, the jacket alone being 5800 t (not including the ram piles for the foundation into the sea bottom). The new central platform 2/4J consists of a 11400 t jacket tied to the sea bottom by 16 ram piles of a total weight of 5500 t and carries the deck with a weight of 23000 t. The two platforms stand about 90 m above sea level and are connected to each other and the total complex by several bridges.

- Petronius Tower
  Today, the Petronius Tower with an overall height of 564 m is the highest (or better: deepest) offshore platform in the world. It is situated in the Gulf of Mexico, around 200 km from New Orleans. This big project was only successfully completed because of the application of high-strength steel of the S460M-Offshore (about 2200 t used) in the area of especially constructed elastic flexible joints. These flexible joints permit the tower to adapt to the movement of tides and waves. The plate thickness used for this construction was 90 mm.

- Siri
  Siri is situated in the north-western part of the Danish sector of the North Sea, around 220 km from the coast. The 104 m-long legs have an outer diameter of 3.5 m and a single weight of 800t. The jacking system is characterised by a special locking mechanism, which enables the platform to be temporarily a fixed structure. The steel grade S690Q-

Offshore, for which improved fracture toughness properties had to be approved, was used for the first time in this type of construction.

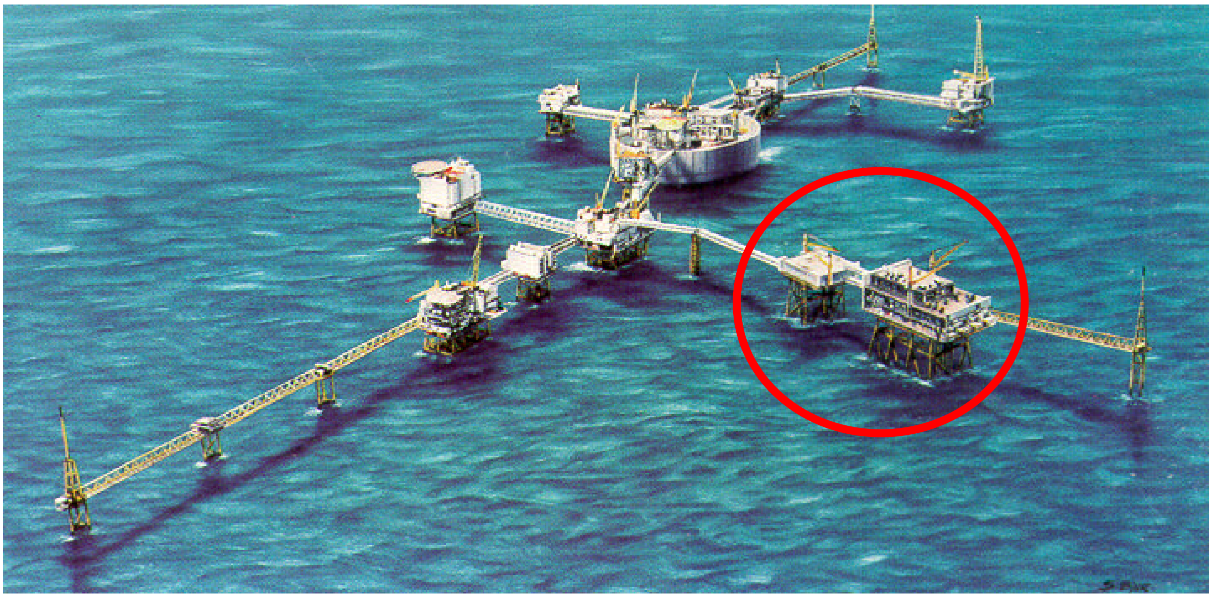

Figure 17: Heavy plates for offshore platforms, Ekofisk II.

At present the offshore grade S500TMCP, for which the same toughness properties as for lower-strength steels are required, is being used for the first time e.g. in the Grane-project in Norway. In addition, the high yield strength grade S690Q-Offshore is more and more being used. However, many questions remain concerning crack resistance and corrosion fatigue prior to an expansion in the use of these very high-strength steel plates.

Perspectives

Today, the designers of structural steelwork and offshore structures can choose from a nearly unlimited selection of heavy plates with regard to dimensions and steel grades.

Plate Dimensions:

- thickness between 8 mm and 250 mm
- width between 300 mm and 5200 mm
- length between 6000 mm and 36000 mm
- weight of single piece up to 60 t

Microalloyed steel grades:

- Fine-grained steels N — S275N - S460N incl. offshore-grades
- Fine-grained steels TM/TMCP — S355M - S460M incl. offshore-grades
- Water quenched and tempered structural steels — S460Q - S690Q incl. offshore-grades

Using this selection nearly unlimited opportunities are offered to designers to combine optimal dimensioning and design of the building as well as efficient fabrication properties to provide an economical and competitive construction. The current selection of plate products can fulfil customer demands and desires for the coming decades.

The future developments within heavy plate technology related to structural steelwork and offshore construction are characterised by the user's desire of facilitating further reductions in fabrication costs. Additional requirements with regard to the homogeneity of the mechanical and chemical characteristics to the dimensional tolerances and flatness signify a great challenge for the processing and rolling technologies of heavy plates.

Summary

The paper has reviewed the most recent development of production technologies for structural steel plates. The synergistic effects between microalloying and TMCP have been explained. The application examples described covered the range of plate dimensions and plate properties. The balanced combination of properties emphasises the importance of weldability, strength and toughness.

The principal driving force for the development of microalloyed heavy structural steel plates has been the economics of both production and application. Both have required a great deal of research and investment in order to create the present range of products by exploiting the possibilities of what may be termed a "Multiflex-Mill".

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