1. **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 (order thicknesses may range from 5 to 500 mm and widths from around 1 to 5 m may be selected);
- possess the yield and tensile strength figures required by the designers (yield strengths from around 235 N/mm$^2$ to above 1100 N/mm$^2$ can be specified);
- possess the toughneces required by designers even, in many cases, at low temperatures;
- possess good workability (e.g. deformability and weldability);
- if required, possess resistance to corrosion resulting, for example, from attack by the hydrogen contained in H$_2$S-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 an extreme combination of alloying and processing technologies, only as a result of comprehensive development work and plant investments.

The technological status of present-day heavy plate production is discussed below. Slabs or ingots of appropriate size (continuous-cast strand thicknesses of up to 400 mm and cast ingot thicknesses of up to 1000 mm) 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 test and inspection operations.

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

The heavy plate producer must have qualified staff, efficient plant installations and suitable control and instrumentation systems for all these 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 consists, in addition to the plates, of comprehensive process data registered for the purpose of quality monitoring.
and evaluation, and of 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.

2. The process stages from a metallurgical viewpoint

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.

![Figure 2: Process steps in the plate mill and their metallurgical objective](image)

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 and is further intensified as a
result of structure transition and precipitation processes during the subsequent cooling phase, depending on rate of cooling. The plates are generally hot-stacked in the lower cooling range in order to ensure effusion of hydrogen. 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.

3. 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 hearth bogie 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](image)

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 hearth bogie 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 on the reversing pattern in widening and elongating passes. Figure 4 shows plant-hardware details and, in particular, the large roll body length of 5.5 and 4.8 m, 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 reduction rates of up to 50 mm. Special control and measuring facilities to ensure adherence to tight thickness tolerances include the AGC (automatic gauge control) and the thickness measurement system. WORB (work roll bending) and BURB (backup roll bending) are available for control of flatness, and a process model for drafting of the pass sequence. Particular process flexibility is achieved by the spacing of 105 m between the two stands.

<table>
<thead>
<tr>
<th>Roll stand design:</th>
<th>features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
</tr>
<tr>
<td>5.5m</td>
<td>4.8m</td>
</tr>
<tr>
<td>1985 (MDS)</td>
<td>1971 (SECIM)</td>
</tr>
<tr>
<td>max. 108000kN</td>
<td>max. 90000kN</td>
</tr>
<tr>
<td>max. 2 x 4500kNm</td>
<td>max. 2 x 3200kNm</td>
</tr>
<tr>
<td>AC synchr.</td>
<td>DC</td>
</tr>
<tr>
<td>max. 7m/s</td>
<td>max. 6m/s</td>
</tr>
</tbody>
</table>

Figure 4: Rolling stand design

Cooling can be accelerated with water cooling on the so-called MULPIC (MULti-Purpose Interrupted Cooling) installation as an alternative to cooling of the rolled product in air. This 30 m 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 on the hot-
straightening machine, with the application of forces of up to 3000 to.
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 (high shape 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 rolling, the center of the rolled product is also thoroughly reshaped and the foundation thus laid for good toughness properties or high cross-section reduction at fracture values in the direction of the plate thickness. LP (longitudinal profile) rolling should be mentioned at this point as a special variant of shaping. As shown in the schematic in Figure 6a, the hydraulic screw-down control system of the AGC is used in this case not to ensure a constant rolled thickness but instead to achieve a defined longitudinal profile (profiles suppleable shown in Figure 6b). Profiling fulfills the requirements of load cases in structural steel engineering while optimizing design weight.

4. 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.

The most important variants are compiled and compared in a temperature/time diagram in Figure 7:

4.1 Classical processes: Rolling + heat treatment

The first group of variants is based on the "normal rolling" process described above (with no special temperature control of the rolling process):
Rolling Shape Factor = \[ \frac{2 \cdot \sqrt{R/(t_0 - t_i)}}{t_0 + t_i} - m \]

Reduction = \[ \frac{t_0 - t_i}{t_0} \times 100\% \]

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

a) \( \epsilon_t = 1.71 \) (250→146mm) / 12 passes  

b) \( \epsilon_t = 1.71 \) (250→146mm) / 3 passes

Figure 5: Influence of per-pass reduction on deformation and properties
Figure 6a,b: Longitudinal profiled plates: diagram of production (schematic) and examples of possible profiles
Figure 7: Temperature time scheme for different process variants

**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.:

**Variant B:**

Normal rolling + heat treatment “Austenitization (>Ac₃, approx. 900° C) + cooling in air” = Normalizing (N)

This is performed in correspondingly dimensioned 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 perlite. The delivery state is abbreviated to "N". Higher yield strengths and tensile strengths can essentially 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 final deformation in the N- temperature range, which is therefore also designated as “N”. Steels in state “N” are used, among other things, for boiler and pressure-vessel making, in particular.

**Variant C:**

Normal rolling + heat treatment "Austenitization (>Ac₃) + water quenching”
= Quenching (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 delivery state is abbreviated to “Q”.

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 Ac₁ -100° C, i.e., approx. 600° C). A heat-treated structure with a combination of a still relatively high hardness or yield strength and tensile strength with a systematically adjusted toughness.

Quenched and tempered steels are used in particular where requirements for strength or resistance to wear are especially high.

**4.2 Thermo-mechanical treatment processes**

The demands for high yield and other strengths in large-diameter linepipes (low wall thicknesses and high conveying pressures in the case of natural gas), combined with high toughnesses at low temperatures and good weldability, have resulted in the development of “Thermo-Mechanical rolling”, the extremely diverse forms of which can nowadays be grouped together under the umbrella term “TM” (or TMCP = Thermo-Mechanical Control Process).

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 systematically for the achievement of the specific combination of properties required. TM rolling can therefore be defined as a process which aims at achieving a structure with a fine effective grain size,
permits 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-recrystallizing 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).

This brief definition requires further explanation. The essential benefits of TM rolling are based on the effects of micro-alloying, for example niobium (Nb), which achieves its full effect even at low content levels of 0.02 to 0.05 %, viz.:

- Niobium retards or suppresses recrystallization of the austenite (reformation of the grains between the individual rolling passes). The deformation effect of a large number of passes at temperatures of around <850°C is thus accumulated, permitting the formation of very-fine grains during transformation.
- During the course of the process, niobium forms carbonitride precipitations which block displacements in the atomic lattice and thus result in increases in yield strength and tensile strength.

These two effects of Nb can be exploited by means of process adaptation and make it possible to reduce alloying element contents and C content to such an extent that high toughness values and good weldability can be achieved at identical or higher yield strength and tensile strength.

The exploitation of strengthening mechanisms to best achieve the specified property profile by means of “microstructure breeding” can be accomplished by means of an appropriate range of equipment in the rolling mill. As Figure 7 shows, it is therefore possible to differentiate between a number of basic TM variants, the delivery state being abbreviated, in accordance with the relevant standard, to "M".

For Variants D and E, the mechanisms mentioned are controlled in 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 drawn down into the γ→α (ferrite) transition range (E). This makes it possible to achieve tensile strength- and yield strength-enhancement by “cold deformation”. Cooling of the plate is in air in both cases.
In the case of Variants F and G, rolling is performed on a pattern similar to that for D or E; in order to achieve a modified structure, for increasing plate thicknesses, in particular, 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 plot selected, as shown in Figure 8:

Variant F: In the case of ACC (accelerated cooling), cooling as shown in Figure 8a is used and results in cooling with ideal cooling rate.

Variant G: In this case, fastest possible cooling of the surface, similar to conventional quenching (Variant C), is applied. In the DQ (Direct Quenching) case, the center of the plate is also cooled to below the martensite-starting temperature by means of continuation of cooling (Figure 8b). In the QST case, the center heat still present is exploited after an extremely short cooling time, and self-tempering is achieved (Q + self tempering), (Figure 8c).

![Diagram of cooling process - aspects and variants](image)

**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 normalized state are shown in Figure 9. The gains in yield strength and strength compared to N achievable by means of TM + ACC or DQ are shown for a given plate thickness (25 mm) and a micro-alloyed steel composition with a low C equivalent.

Figure 9: Comparison of strength properties for different processes

All important process parameters (Figure 10) and their implementation via process control are necessary for technological achievement of the TMCP process.

The essential stages of the TM process-hardware can be traced in the plant layout of the hot zone of the Dillingen rolling mill (Figure 3):
- Slab reheating 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 physical models of complete slab heating. The technical equipment and performance of the reversing four-high rolling stands are decisive for the deformation process. High rolling forces are necessary, for TM pass sequences with low final rolling temperatures in particular. 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, under 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 120 mm) 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 high cooling-intensity flexibility. The expansion form of the MULPIC cooling system selected, with a high-pressure section, is characterized by: Water-cushion cooling of the plates from a series by means of upper and lower ramps fitted above and in the roller table, high variability of water flow, from 70 to 2500 l/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 for 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 achievement of homogeneous application of water.

Figure 11: Control diagram of the MULPIC cooling device

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 and, for a number of years now, for shipbuilding and structural steel engineering (bridges and offshore drilling platforms). The materials-relevant advantages of these steels are discussed in other reports.
Common to all the process variants examined above, and particularly true of the more recent variants, 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 in fact permitted, but must be achieved with statistical certainty, i.e., repeatably, and in all cases demands good knowledge of the underlying metallurgical interrelationships and adjustment of all process parameters with defined standard deviations, both during steelmaking in the steelplant, i.e., adherence to the target composition, and also during the TM rolling process, including cooling, and on-line monitoring and approval systems.

5. **Further process stages up to the completed plate**

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 stations 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 |
| • 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 processes may be necessary on the hot or the cold plate, depending on flatness specifications. Stacking of the plates has a dual role, that of hydrogen effusion and that of buffering upstream the 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 of the edge scrap and cutting of 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 specimen coupons for destructive materials testing, are performed for the purposes of quality monitoring. 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.

6. **Product range**

The product range, which provides an impression of the diversity and flexibility of the processes used, is characteristic of a heavy plate rolling mill. Depending on the process used and the equipment thus necessary, there are direct or indirect weight limits on the dimensions of a heavy plate as a result of weight. The fact that a large number of steel grades, which are described in more detail in standards, codes of practice, materials data sheets and individual customer specifications, is superimposed on this large and diverse range of dimensions is not discussed in any more detail at this point.

7. **Process development as the basis for the achievement of modern specifications**

The production process for heavy plate includes many diverse potential 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 with the user. The wishes expressed to the heavy plate producers by customers with respect to product properties, and dimensions, in particular, and also working 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.
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