As an example for such tailor-made plates the longitudinally tapered plates should be mentioned.
It has to be emphasized that quality assurance systems and the feed-back from the fabricator or user side to the plate producer are key points for the well-controlled development of process and product.

1. INTRODUCTION

Dillinger Hüttenwerke (DH) is operating a plate mill with 2 powerful four-high stands using slabs and ingots from their own steel shop. Together with all the other equipment which has been installed during the last two decades in the plate mill, the application of a great variety of processing routes has been enabled.
As an important supplier of several large-diameter-pipe mills all over the world, DH entered into the production of TMOP materials already more than 15 years ago, in parallel to the production of heavy plates for a wide range of applications made by various rolling and heat treatment variants.
Figure 1 gives an illustration of the development of production tonnage during this recent history.
Whereas the importance of TM-rolling especially together with ACC has been highlighted in other papers 1,2) this presentation will focusize on those processing variants which allow to meet special combinations of customer’s product requirements both in terms of geometry and physical properties.
These product groups will be according to Table 1:

<table>
<thead>
<tr>
<th>Table 1: Special product and process variants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product</strong></td>
</tr>
<tr>
<td>Plates with extreme size</td>
</tr>
<tr>
<td>Plates with extreme thickness</td>
</tr>
<tr>
<td>Plates with variable thickness</td>
</tr>
<tr>
<td>Plates with unusual heat-treatment</td>
</tr>
<tr>
<td>Plates with substitution of N-heat-treatment</td>
</tr>
</tbody>
</table>

Figure 1: Plate production - Development of tonnage per year
• plates with extreme size
• plates with extreme thickness
• plates with variable thickness
• plates with unusual combination of heat treatment cycles or substitution of heat treatment by rolling schedule design
• and finally the possibilities of combining these features.

Fig. 2 gives an illustration of the various process stages which contribute more or less to the geometrical and physical product properties.

2. PLATE MILL LAYOUT AND EQUIPMENT

The layout of the plate mill (Fig. 3) is determined by the following design features:

• sufficient and flexible reheating facilities: 3 pusher type furnaces, i.e. up to 7 slab rows can be charged in parallel,
• 3 bogle hearth furnaces, esp. for ingots or small size slabs or non-ferrous materials
• high pressure descaling unit (180 bar) in front of the stands
• 2 powerful 4-high reversing stands (Fig. 4) first: 5.5 m barrel length, mainly for pre rolling including breadside rolling second: 4.8 m barrel length, for finish rolling
• both: automatic gauge control for thickness control and roll bending devices for flatness control
• process control: PLATE model for pass schedule calculation
• space between stands: 105 m
• MUPIC-ACC-equipment: 30 m long water pillow system for accelerated cooling or direct quenching
• 5.2 m hot leveller
• heat treatment facilities for normalizing, quenching and tempering
• in-line automatic US-testing (100 % body testing)
• 2 shearing lines (up to 52 mm thick plates)
• torch-cutting (for heavy thickness range)
• cold levalers
• shot-blasting (+ painting)

The principal material flow during plate production occurs along 1 hall of 1.2 km length.

Figure 2: Contribution of process steps to product properties

Figure 3: Plate Mill - Layout (Rolling part)
efficiency. When the 5.5 m-stand is used as a finishing stand, plates up to approximately 6.2 m width can be delivered. For large diameter pipe mills the production of 64 inch-pipes has been enabled with plates from Dillingen, and for general structures or large vessels such wide plates allow to spare welding work.

During specifying the technical features of the stand a lot of very different application cases had to be regarded. The most important of them are illustrated in Fig. 5 in terms of rolling force and torque situation. This covers normal hot rolling of plain carbon manganese steel plates which get their final properties by additional heat treatment. Thickness reduction per pass is in the range of 30 to 40 mm due to relatively high rolling temperatures; only for extreme cases, e.g. low total reduction from slab to plate the single reductions are increased up to 60 mm.

The purpose of such rolling technique will be explained later in this paper (chapter 3.2). In the case of TM-rolling the finishing passes are applied in the range of Ar3 or even at lower temperatures, i.e. without softening in the interpass times by recrystallization due to microalloying of high strength steels. As a consequence, even with reductions as low as 10 mm, the rolling loads are considerably greater than those during normal rolling. The torques become high even with moderate forces when they are combined with high thickness reduction.

That is why the 4.8 m-stand and its motor were prepared for max. torques of 3200 kNm per roll and the 5.5 m-stand even up to 4500 kNm per roll based on a synchronous type of drive motor.

Further user orientated application examples of the equipment are presented in the subsequent chapters. As shown in Table 1 each special product group has been based on a process design exploiting the possibilities of the installed equipment.
3. SPECIAL PROCESS AND PRODUCT VARIANTS

3.1 Plates with extreme size

One prerequisite for the production of plates with extreme weight and size is the design of the rolling equipment as described above. The second base for such products is the available material to be put into the reheating and rolling process. Table 2 presents a list of slab and ingot sizes coming from the steelmaking plant at Dillingen which is located at a distance of less than 1 km from the plate mill. The gap between the both is used for the slab finishing and storage, i.e. slab yard. These circumstances are also favourable for warm or hot charging of CC-material. As each plate is rolled due to ordered dimensions which can vary extremely, a large variety of slab and ingot sizes is necessary to assure in all processing stages a safe and reproducible handling.

Table 2: Slab and ingot sizes for plate production

<table>
<thead>
<tr>
<th>Slab/Ingot</th>
<th>section mm x mm</th>
<th>Spec. weight/m²</th>
<th>max. weight t</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC-slab A</td>
<td>2200 x 300</td>
<td>5.0</td>
<td>27</td>
</tr>
<tr>
<td>* B</td>
<td>2200 x 250</td>
<td>4.3</td>
<td>23</td>
</tr>
<tr>
<td>* C</td>
<td>2200 x 200</td>
<td>3.4</td>
<td>18</td>
</tr>
<tr>
<td>* D</td>
<td>1550 x 250</td>
<td>3.0</td>
<td>16</td>
</tr>
<tr>
<td>* E</td>
<td>1550 x 200</td>
<td>2.4</td>
<td>13</td>
</tr>
<tr>
<td>Ingot I</td>
<td>2510 x 910</td>
<td>-</td>
<td>55</td>
</tr>
<tr>
<td>* II</td>
<td>2125 x 875</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>* III</td>
<td>1830 x 710</td>
<td>-</td>
<td>23</td>
</tr>
</tbody>
</table>

(slab length range for pusher type furnaces: 1.8 to 5.4 m)

Due to the ordered delivery condition, e.g. as rolled, normalized, quenched and tempered, TM-processed, ..., a range of available plate sizes can be defined and collected in the delivery program (Fig. 6).

As a result the utmost limits of the production program cover thickness from 5 to 420 mm, width from narrow lamella to 5.2 m, length rolled up to 48 m, delivered up to 36 m and 28 m for heat-treated plates, and all this in a large variety of steel compositions and grades which are not dealt with here in more detail. It should be mentioned that extreme plate sizes and weights require the appropriate transport facilities both in the mill which include cranes, roller tables, trucks and railway systems and also for the transport to the customer which include special trucks or wagons for inclined transport of large width plates and ship transport from Dillingen's harbour.

As an additional service to the customer plates can be delivered shot-blasted and painted and even with edge preparation or preforming by the DH fabrication shop.

3.2 Plates with extreme thickness

For almost three decades the advantages of continuous casting have been already exploited to produce heavy plates with an optimized level of homogeneity both over thickness and length of the product. By using CC-slabs also bottlenecks in steel and plate production coming from the complications with ingots could be avoided and the yield of the whole process has been brought to a considerably higher level.

The use of CC-slabs is restricted to a certain maximum plate thickness. A defined total reduction ratio, that means slab to plate thickness, is necessary in order to meet the property requirements on plate. The required total reduction ratio depends on the level of properties that has to be met, the features of the starting material (slab) and on the rolling process itself.

A sophisticated and "safe" production route is required for production of thick plates, e.g. 125 mm starting from CC-slabs with thickness 300 mm, which corresponds to a total reduction of 2.4 times. "Safe" means plates with satisfactory internal quality both
in terms of soundness (no harmful porosity) and of properties even in the core (especially of toughness and through-thickness-properties).

To achieve this goal, it is necessary to apply a rolling process which ensures to get also in the core of the material a local deformation comparable to the nominal deformation. The essential parameter of the rolling process describing its efficiency in penetration of deformation into the core is its shape factor m (Figure 7).

One prerequisite to perform rolling with high shape factor (abbreviated: HS-rolling) is a powerful rolling stand. For example, at the 5.5 m - 4-high stand of Dillinger Hütte which enables rolling up to a maximum force of 108000 kN and torques up to 4500 kNm a reduction per pass of up to 80 mm can be performed. The efficiency of HS-rolling can be increased by low speed rolling, which is only possible with suitable roll bearing systems.

Figure 8 demonstrates the effect of the HS-rolling on the reduction of area values in through-thickness direction. It clearly appears, that by using HS-rolling instead of normal rolling, that means low shape factor rolling (LS), the reduction of area can be considerably improved for a given total reduction ratio and for a defined steel type and cleanliness level.

As the HS-rolling is applied to use CC-slabs in competition to ingots for a certain thickness range, it also allows to extend the possible plate thickness range for a given ingot thickness (e.g. 800 mm) and defined plate requirements to higher values. Another application example can be seen in the first rolling stage of TM schedules where the HS-rolling assures a complete recrystallization of austenite in the core of the material 4). This is an important contribution to the grain refinement and thereby to a high level of strength and toughness.

3.3 Longitudinally tapered plates

One feature of performance of a plate mill has to be seen in the accuracy and homogeneity of thickness over the whole length of each plate. To avoid thickness deviations along the plate, sophisticated
control mechanisms and their technical realization have been implemented. They are well-known as AGC (automatic gauge control) systems with various modes of application (relative, absolute, feed forward, ...). Based on this technique of control of defined constant thickness over plate length, another exploitation of the system was created by using it for the production of variable plate thickness over length.

From the construction point of view a lot of structural components like beams, box girders or similar parts, e.g. in bridges have to bear load distributions which are changing over length.

The answer of the plate producer are LP-plates, i.e. longitudinally tapered plates 5, 6). They allow to reduce costs by decreasing the weight of the whole construction or the number and extent of weld seams and machining of transition parts. These advantages compared to the conventional construction case are illustrated in Fig. 9.

**Figure 9:** Advantages of LP-plates

The maximum values for thickness change and gradient have been recently increased to 55 mm and 8 mm/m respectively.

From the process point of view, Fig. 10 explains the principle of the method. The desired profile is fed into the process computer. The rolling is performed in a reversing mode by increasing the defined deviation from parallel faces pass by pass. The thickness deviation for each longitudinal position is applied via the AGC-positioning system, i.e. a hydraulic oil/grease system, the data of which are described in Table 3.

**Table 3:** Data of AGC (automatic gauge control) on 5.5 m-4-high stand

<table>
<thead>
<tr>
<th>Hydraulic roll positioning system (AGC)</th>
<th>MDS-SERMES (oil/grease system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>MDS-SERMES (oil/grease system)</td>
</tr>
<tr>
<td>Main piston diameter</td>
<td>1210 mm</td>
</tr>
<tr>
<td>Main piston stroke</td>
<td>40 mm</td>
</tr>
<tr>
<td>Plunger piston diameter</td>
<td>382.6 mm</td>
</tr>
<tr>
<td>Plunger piston stroke</td>
<td>400 mm</td>
</tr>
<tr>
<td>Amplification ratio</td>
<td>10</td>
</tr>
<tr>
<td>Servo-cylinder diameter</td>
<td>580 mm</td>
</tr>
<tr>
<td>Nominal load</td>
<td>100,000 kN</td>
</tr>
<tr>
<td>Maximum load</td>
<td>130,000 kN</td>
</tr>
<tr>
<td>Grease pressure</td>
<td>max. 565 bar</td>
</tr>
<tr>
<td>Nominal oil pressure</td>
<td>250 bar</td>
</tr>
<tr>
<td>Servo-valve type</td>
<td>Moog DD 79-265</td>
</tr>
<tr>
<td>Nominal oil flow</td>
<td>800 dm³/min</td>
</tr>
</tbody>
</table>

**Fig. 11** shows a variety of different profile forms which can be selected according to the load distribution of the structural component. Subsequent to the final rolling pass the required flatness is assured by warm levelling. In this process stage the upper rolls have to be able to follow the right profile.

**Figure 10:** Principle of LP-plate rolling
The mostly performed applications for process route are:

- Austenizing plus water cooling with hot-leveling either before or subsequent to the cooling
- Reheating at defined temperature plus rolling plus cooling plus an additional heat treatment (e.g. tempering) in ELO

In respect to the customer’s plate requirements and other important aspects shown in Fig. 12, the following MULPIC process variants can be applied:

**Figure 11:** Types of thickness profile for LP-plates

The benefits of LP-plates have been recognized by designing engineers. Therefore several structures can be shown as successful application examples of this by-product idea of process development.

**3.4 Heat treated plates involving ACC-treatment**

**Figure 12:** Design of cooling process

- ACC-treatment with predefined cooling rate or with "ideal" cooling rate aiming for a cooling of the core as quick as possible but with a cooling stop temperatures for surface just above martensite start temperature 2).
- NQ, or in special cases DQ with high cooling rates and cooling stop temperatures for surface and core below Ms 9).
- QST with high cooling rate for a short time to bring down the plate temperature only in the surface region below the martensite start temperature and subsequently with switched-off cooling for self-tempering of this microstructure by the heat coming from the core of the plate.

The courses of temperature for these process variants are precalculated by an offline cooling model and stored as cooling
schedules. The MULPIC process control (Fig. 13) guarantees a sufficient accuracy and reproducibility of the cooling process, good homogeneity of properties and satisfying flatness of the final product.

The following examples for application demonstrate the range of flexibility for each production route:

**NO/DQ**: Using the ELO-MULPIC-process route, NO-process can be performed for plate thicknesses above 30 mm, width up to 4500 mm, plate length up to 18 m and a maximum specific weight per meter of 4 tons.

**QST**: An illustrative example is the application of the QST-process for thick plates with defined hardness profile from the surface to the core combined with severe flatness requirements. The dimensions of the treated plates are: thickness: 170 mm, width: 3000 mm, length: 10 m. On the one hand hardness on surface has to be adjusted above 245 HV10 because of high wear resistance requirement, on the other hand a steep hardness gradient from surface to core is desired to get a good machinability for the core. Flatness deviation has to be adjusted to equal or less 8 mm per total plate length (of 10 m). Fig. 14 shows the calculated and measured temperature course for the applied QST-process with the temperature drop of the surface layer for a short time below martensite start temperature and the recovering and self-tempering process after end of cooling. As a result of QST, a defined martensite/ferrite-perlitic microstructure distribution and a hardness profile over the plate thickness with a difference of 100 HV10 has been adjusted. Flatness is for 95% of plates within the required range already without additional flattening.

![Figure 14: Temperature profile during QST-process and hardness distribution over the plate thickness](image)

### 3.5 Normalizing rolled plates

In order to avoid normalizing treatment in the furnace as well as to reduce production time, normalizing rolling can be applied. Normalizing rolling has been defined in standards like SEW 082 or BS 4360. Following these and other definitions, N-rolling means a rolling procedure with the
final deformation at well defined tempera-
tures above the Ar3-temperature, that means
in the γ-region, typically in the normalizing
temperature range. As a result, the material
condition is generally equivalent to that
obtained by normalizing. Therefore normal-
izing rolled plates can be normalized (e.g.
due to hot forming process) without risk to
fail the specified mechanical properties of
the steel grade.
Concerning the equivalency from N-rolling
and N-treatment in the furnace, more
detailed definitions have been given for
supervised steel applications like for
pressure vessels by the VdTÜV material
sheets. To assure both the material prop-
erties in N-rolled and N-treated condition
within the specified limits and their
differences in the range of equivalency, it is
necessary to apply a sophisticated process
design approach.

Fig. 15 illustrates the interference of the
effects of chemical composition and rolling
process parameters to gain properties at the
target value c within a tolerance of ± d.
Taking into account both the slab com-
position and the actual rolling parameters
during on-line process with support of a
metallurgical modelization, the properties
can be predicted and compared to the
specification. In the case of risk for non-
conformity a test of the individual plate is
initiated before decision on release.
The performance of the model has been
checked and confirmed on a statistical base.

Fig. 16 and 17 give evidence and confidence
for the prediction quality and the assurance
of the equivalency criteria.

Fig. 16: Comparison of measured and
calculated YS-values for N-rolled
condition

Fig. 17: Comparison of N-rolled to N-
treated condition

Beside these aspects of property control,
other advantages of N-rolling should be
mentioned. As there is no need for a furnace
treatment, plate sizes as they can be rolled
and transported have been made available in
condition N via rolling at the stand with barrel
length 6.5 m, passing restrictions in furnace
geometry.
Compared to plates normalized in the
furnace, normalizing rolled plates have a
better surface condition because there is no
additional oxidation of the surface due to
reheating after rolling.

3.6 Combination possibilities of the
presented processes

After the presentation of the specific process
routes having been developed to deliver
products with a combination of properties
superior to classical hot rolled heat treated
plates, there remains the question of further
development steps. Not entering deeply into
the topic of future potential in this chapter, it
should be looked for possible combinations of the above presented process routes and ideas. Such combination examples are:

a) Longitudinal profile + N-rolling,
b) Special ACC route after austenizing in furnace (e.g. to reproduce TMCP properties),
c) HS-rolling + interpass ACC (to cool the surface region allowing stronger penetration of the deformation into the core),
d) HS-rolling for clad products.

It becomes evident that already today several of the combination possibilities are exploited during production of a significant quantity, e.g. by HS-rolling applied to CC-slabs for extreme final plate thickness (which would require ingots, if HS were not possible) or N-rolling applied to plates with extreme width or length (which cannot pass through a furnace with restricted dimensions) or rolling and processing of non-ferrous materials (using the flexibility in working range of the equipment and of the on-line process control).

4. CONCLUSIONS

The presentation has shown how DH has implemented various equipment and facilities to allow production of tailor-made plates for the needs of different users. It has to be mentioned that some of the process routes have only been developed after systematic comparison of real needs from the user side and possibilities of the producer side. As a consequence we expect that the both sides together will introduce or derive further production ways with benefits for both of them.

References:

1 Streßelberger A.; Oswald W.; Bauer J.; Hanus F.: Stahl u. Eisen 111 (1991), Nr. 5, pp. 65-73