DEVELOPMENT, PRODUCTION AND APPLICATION OF HEAVY PLATES IN GRADES UP TO X120

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ABSTRACT

This paper gives an overview of the development of heavy plates in super-high strength steel grades at the 5.1 meter heavy plate mill of Mannesmannroehren Muelheim GmbH (MRM). MRM is a subsidiary of the second largest German steel producer Salzgittter AG. The requirements of Mannesmann's customers in the field of high strength plates as the major input to the R&D strategy are summarized. Results of laboratory trials, semi- and full-industrial plate production are shown. Different applications of super-high strength plates coming from MRM are described. The development of super-high strength steel plates at MRM is used as an example which shows the company's strategy of using a very short chain from market requirements via research and development and industrial trials to series production for customers.

KEYWORDS

Mannesmannroehren Muelheim; Heavy Plates; TMCP; Accelerated Cooling; X100; X120; CMnNbTiB-steel

INTRODUCTION

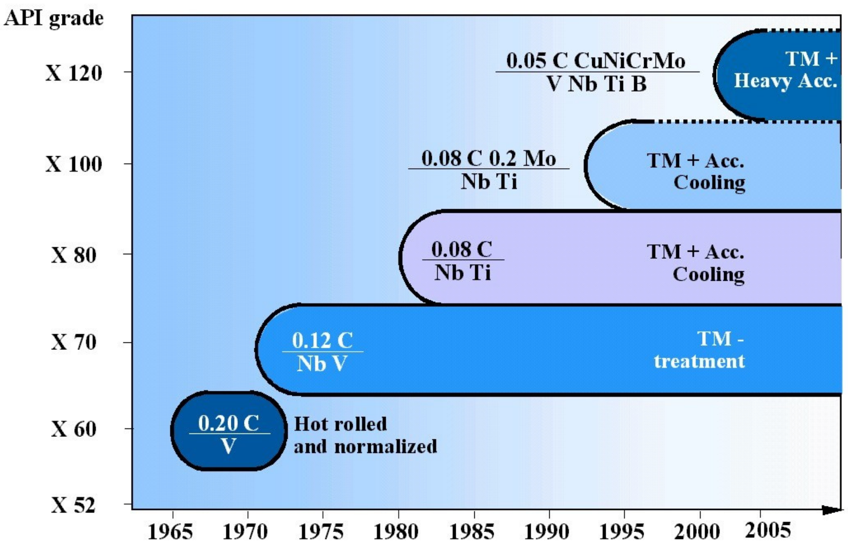
Mannesmannroehren Muelheim (MRM) in Muelheim, Germany, runs a heavy plate mill with a roll width of 5.1 meters (Figure 1).

Over the last decades MRM specialized more and more in thermo-mechanical processing (TMCP) mainly for pipe and structural applications. For some of these applications, the market requirements are changing in many ways. There is a tendency to high and super-high strength steel grades which bears a couple of advantages for customers of plate mills. The major benefit of increasing yield strength levels is the possibility to reduce the wall thickness which in most cases means reducing the weight of a structure. Taking pipe making as an example, a plate customer who decides to choose higher steel grades can choose between different advantages. On the one hand he can reduce the pipe weight by lowering the wall thickness. Hence, material-, handling- and welding costs are decreased. On the other hand for a given wall thickness, the pressure of the transported medium can be higher which increases the output of a pipeline. By a possible change in pipe geometry and/or pressure, an optimum layout of a pipeline can be achieved.

Fig. 1: Rolling stand

These advantages were pointed out decades before when the strength levels in the pipe business were shifted from API X52 manufactured from hot rolled and normalized CMnV steel plates to X60, X65 and X70 (see Figure 2). The latter strength levels became possible by the development of thermo-mechanical processing (TMCP) of i.e. CMnVNb steels. In the eighties of the last century, steel grade API X80 was developed by implementing TMCP plus accelerated cooling (ACC) of CMnNbTi steels. The first X80 pipe line of the world was installed in 1992 in Germany [1]. The pipes for that project were produced and delivered by Mannesmann (the later Europipe) who promoted the major development of X80 plates and pipes in the eighties and nineties. Since these days, the heavy plate mill of Mannesmannroehren Muelheim produced more than 200,000 t of plates for pipes in API X80 or the European equivalent L555. This total tonnage of X80 shows that the production of X80 plates nowadays is daily business at MRM plate mill.

Fig. 2: Development of HSLA pipeline steels



In the mid nineties of the last century, the next step on the way of increasing strength levels was done. Several pipe producers over the world required plates for the first semi-industrial X100-pipe productions. One of these pipe manufactureres was Europipe, which is a subsidiary of Salzgitter/Mannesmann and Dillinger Huette. MRM delivered plates of API X100 strength level to Europipe. They were used for the manufacturing of X100 pipes of 28" diameter and 19.1 mm wall thickness [2]. Several trial productions followed during which Mannesmann/Europipe gained a detailed knowledge of the possibilities and challenges of the manufacturing of X100 plates and pipes.

Consequently, the next step was to look for steel grade X120. Europipe reported on possible future market requirements for even higher strength levels than X100. Salzgitter Mannesmann Forschung, which is the research and development center of Salzgitter, developed concepts how to manufacture plates and pipes of grade X120 and achieved laboratory results which were promising. Hence, MRM decided to perform a large scale production rolling at the Muelheim plate mill.

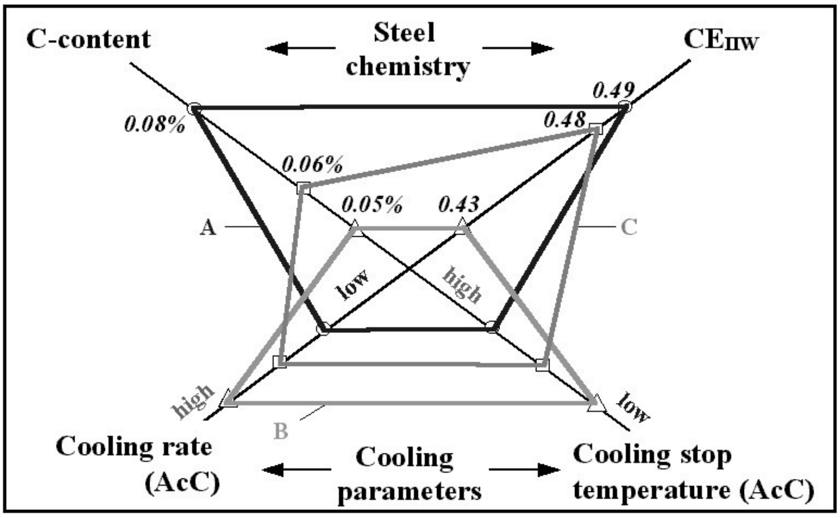
All these above mentioned developments from a customer requirement to a finished product were performed in a very close cooperation within and between the companies Salzgitter/Mannesmann and Europipe. In all cases the basic idea for a new product came from the end customer and was instantly brought to MRM's attention by sales and technical service managers of Europipe. Research engineers of Salzgitter Mannesmann Forschung as well as MRM immediately started their development work in order to get suitable plates available for Europipe's pipe production. In the following, several examples are given, how this development chain worked in the field of super-high strength plates and what the results are.

PLATES FOR PIPES IN GRADE API X100/S 690 MC

To cope with market requirements for enhancing strength the development of API grade X100 was promoted within the Mannesmann/Salzgitter Group since 1995. The best possible application of existing technologies was involved in the production of grade X100 plate in laboratory and large scale. As a result it became obvious that the production window for this high strength steel grade is quite narrow [3].

As can be seen from Figure 3 three different approaches were developed with respect to the chemical composition and the process parameters for the thermo-mechanical rolling process during the years of development [4].

Fig. 3: Three different approaches to reach API grade X100



Approach A is characterized by a relatively high carbon content and equivalent of 0.49 as well as a low cooling rate and a relatively high cooling stop temperature. This has the disadvantage that the crack arrest toughness properties are not as high as needed to prevent or even arrest long-running cracks. Besides, pipes produced from plates with a relatively high carbon equivalent can exhibit local areas with reduced heat affected zone (HAZ) toughness. Table 1 gives some results for approach A.

Table 1: Approach A for the production of grade X100 (mean plate values)

heat	pipe size OD X WT	C	Mn	Si	Mo	Ni	Cu	Nb	Ti	N	CE_{IIW}	P_{CM}
I	30” x 19.1 mm	0.08	1.95	0.26	0.26	0.23	0.22	0.05	0.018	0.003	0.49	0.22

heat	yield strength $R_{t2.0}$	tensile strength R_m	yield to tensile ratio $R_{t2.0}$ / R_m	elongation A_5	CVN (-20 °C)	DWTT: SAF @-10 °C
I	717 MPa	780 MPa	0.93	18.0 %	129 J	93 %

Approach B (see Table 2) with a carbon equivalent of only 0.43 was used in combination with fast cooling rates down to a very low cooling stop temperature. This results in the formation of high fractions of martensite in the microstructure, which may have a detrimental effect on toughness properties of base metal. A microstructure typical for very low cooling stop temperature and extremely high cooling speed makes the steel more sensitive to local softening of the HAZ of the later pipe weld.

Table 2: Approach B for the production of grade X100 (mean plate values)

heat	pipe size OD X WT	C	Mn	Si	Mo	Ni	Cu	Nb	Ti	N	CE_{IIW}	P_{CM}
II	30” x 15.9 mm	0.07	1.89	0.28	0.15	0.16	-	0.05	0.015	0.004	0.43	0.19

heat	yield strength $R_{t2.0}$	tensile strength R_m	yield to tensile ratio $R_{t2.0}$ / R_m	elongation A_5	CVN (-20 °C)	DWTT: SAF @ -10 °C
II	727 MPa	807 MPa	0.90	17.9 %	160 J	91 %

All these aspects described above led to the decision to develop an approach C. This approach enables the desired property profile to be achieved through an optimized two-stage rolling process in combination with a medium carbon content, a medium carbon equivalent and optimized cooling conditions. The special potential of the existing rolling and cooling facilities contributes significantly to the success of this approach. This approach ensures excellent toughness as well as fully satisfactory field weldability of the pipes. Approach C combines a medium alloying content right between the first two approaches. Hence, the rolling and cooling schedule was designed accordingly.

Large diameter pipes of all three approaches were produced and due to the results it was decided to follow approach C regarding strength and toughness properties. The work done so far showed the technical and physical limitations for the properties of grade X100. Yield strength and tensile strength can be achieved relatively easy. However, the yield to tensile ratio increases while uniform elongation and fracture elongation decrease. This shows that a simple extrapolation of the conventional requirements coming from grades like API5L X70 is not sufficient.

Basing on the knowledge gained by the lab and mill trials of the last years, MRM was awarded a plate order from Europipe for an X100 pipe project. Approximately 300 meters of plate (12,000 x 3,742 x 18.5 mm) were ordered for pipes being part of a pilot section of a X100 linepipe. The plate requirements in terms of mechanical properties are given in Table 3. They were defined with respect to the change in properties during pipe manufacturing which is well known from experience.

Table 3: Plate requirements

mechanical property	minimum requirement
SMYS	710 MPa
SMTS	760 MPa
CVN @ -30 º C (single/average)	180/240 J
DWTT @ -20 º C (single/average)	75/85 % SAF

Following the results of former trials and tests, a CMnVNbTi steel with additions of CuNiMo was designed basing on the above mentioned approach C. Due to the challenging toughness requirements, a moderat Carbon content of 0.06 % was chosen (see Table 4).

Table 4: Chemical analysis

element	content, %
C	0.06
Si	0.30
Mn	1.90
Nb	0.04
Ti	0.02
N	0.004
others	V, Cu, Ni, Mo
CEV	0.48
Pcm	0.21

Consequently, a two phase rolling schedule with an accelerated cooling from above A_3-temperature down to a cooling stop temperature clearly below 400 °C was used. The chosen cooling rate was in a medium range. This makes sure that the softening effect in the later heat affected zone of the SAW pipe is reduced to a minimum by avoiding a microstructure that would react too sensitive to the heat input during welding. A not too high cooling rate is also reasonable in terms of mechanical properties of the base material.

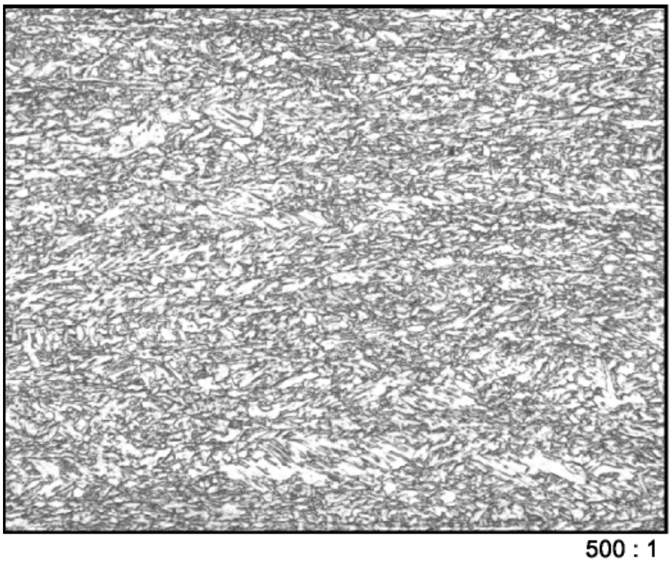
The values of the mechanical tests of the finished plates are summarized in Table 5. All customer requirements were fulfilled.

Table 5: Plate properties

	YT, MPa	UTS, MPa	Y/T, %	A_5 strain,%	CVN -30°,J	DWT -20°,%
min./max.	710/785	760/858	89/97	15/21	185/323	75/100
average	747	797	94	17	251	91

The microstructure consisted of 98 to 100 % bainite partly with a small amount of ferrite. An example is given in Figure 4. This is exactly the microstructure that was planned to receive by the chosen cooling conditions in order to achieve the best combination of properties.

Fig. 4: Typical microstructure



MRM's customer, Europipe, manufactured large diameter SAW pipes from the above described plates. All requirements of the final pipe customer were met. Results are given in Table 6.

Table 6: Pipe properties

	YS	**UTS**	**Y/T**	**A5 strain**	**CVN@-10 ºC (Base-Mat.)**	**DWTT, SAF@-10º C**
average	741 MPa	854 MPa	87 %	15 %	260 J	93 %

PLATES FOR MECHANICAL ENGINEERING IN GRADE S700 MC

Similar to the above described development of plates for pipes, super-high strength plates for other applications were designed. Salzgitter Stahlhandel as the trading company of Salzgitter keeps a wide range of plate sizes and grades on stock (see Figure 5). The yearly shipment is approximately 1.4 million metric tons.

Fig. 5: Storage yard of Salzgitter Trading at its Gladbeck site

Also plates with strength level of 700 MPa are part of its stock. Since TMCP plates have several advantages compared to QT plates (low alloying, excellent weldability etc.) Salzgitter Trading decided to have plates of steel grade S700 MC in stock. Roughly 1,000 t of plates of this grade are constantly in stock. The main applications are mechanical engineering, structural application and manufacturing of yellow goods. MRM, supported by Salzgitter Mannesmann Forschung, designed a suitable alloying and processing system and delivered plates of 20.0 mm wall thickness and a width of 2,500 mm. While all other requirements were similar to those of the above mentioned pipe project, the minimum toughness of 40 J was specified at -40 º C. Besides small changes in the microalloying content, the chemical analysis was similar to the one described above. Hence, the rolling and cooling schedule was similar as well. The results which are summarized in Table 7 fulfilled all requirements of the specification.

Table 7: Plate properties

	YS	**UTS**	**Y/T**	**A5 strain**	**CVN @ -40 ºC**
average	756 MPa	813 MPa	93 %	16 %	210 J

DEVELOPMENT OF STEEL GRADE API X120

In the current line pipe standards a grade X120 with a minimum yield strength of 827 MPa is not yet specified. Therefore, the development of a steel with this SMYS in combination with a minimum tensile strength of 931 MPa was decided to be the main target. A Charpy impact toughness of at least 231 J at a testing temperature of -30 °C was the crack arrest criterion. In the Battelle drop weight tear test the transition temperature for a shear area of 75 % should be lower than -20 °C. The requirements on grade X120 are summarized in Table 8 [5].

Table 8: Target values for grade X120

parameter		**value**	
yield strength		≥ 827	MPa
tensile strength		≥ 931	MPa
CVN toughness	@ -30°C	≥ 231	J
DBTT		< - 50	°C
BDWTT	(SA %) @ -20°C	≥ 75	%
yield / tensile ratio		≤ 93	%
wall thickness		16.1	mm

The required properties of a steel in grade X120 are only reachable with a mainly bainitic microstructure that predominantly consists of lower bainite. Due to the combination of a high dislocation density and very fine scale substructures this lower bainitic microstructure gives the only reasonable option for an ultra-high-strength level in combination with adequate toughness properties. To ensure such a bainitic microstructure the design of the chemical composition and the process parameters have to be considered very carefully to reach the best possible balance between strength and toughness.

To produce a bainitic microstructure especially with a low carbon and low PCM steel the chemical composition had to be designed very carefully. The basic alloying system contains copper, nickel, chromium and molybdenum and the microalloying elements vanadium niobium and titanium. Besides these, the microalloying element boron should also be effective. Boron has a strong retarding effect on the transformation of austenite to ferrite. Hence, it supports the formation of the required bainitic microstructure. To intensify this effect the attention had to be turned to a low carbon content in general. Furthermore, the combination of boron with nitrogen and oxygen had to be avoided.

To reach the best possible combination of strength and toughness properties the grain size of the microstructure should be very fine. The production of such a microstructure was done by a careful choice of the plate rolling process parameters namely the reheating and the finish rolling temperatures as well as the deformation ratios and the conditions for the accelerated cooling.

An optimum reheating temperature leads to the best possible initial austenite grain size which is the starting point for the further control of the mechanical properties during the rolling process. Furthermore, the maximum possible deformation ratio during the first rolling stage is of great importance for a first grain refining of the recrystallising austenite. The finish rolling has to be done close to the Ar3 transition point for a proper control of pancaking of the non-recrystallising austenite. This extremely pancaked austenite has a high dislocation density and transforms into a fine grained lower bainite after the accelerated cooling. For a highly effective accelerated cooling process after finish rolling a cooling rate of above 20 °C/s and a cooling stop temperature below 400 °C are the main process parameters.

A series of laboratory rolling trials was performed to study the influence of process parameters and different contents and combinations of the relevant alloying elements. Especially variations in the contents of carbon, molybdenum, chromium and boron were investigated to characterize the optimum balance of these elements.

The results of the laboratory trials led to a basic chemical composition for grade X120 with a carbon content of 0.035 to 0.050 % and a manganese content of about 1.90 %. Additionally, this steel was alloyed with Cu, Ni, Cr and Mo. The boron content had to be limited in a quite narrow range. The carbon equivalent CE_{IIW} of the chemical composition was in a range of 0.50 % up to 0.55 %. The PCM value was approximately 0.23 %. As can be seen from Table 9, with this analysis and appropriate process parameters the target values for strength and toughness properties were successfully achieved.

Table 9: Mechanical-technological properties of laboratory plate material in grade X120 [6]

mechanical properties			**mean values transverse**
yield strength (round bar)	$R_{t0.5}$	(MPa)	843
yield strength (round bar)	$R_{p2.0}$	(MPa)	1087
tensile strength (round bar)	R_m	(MPa)	1128
yield-to-tensile ratio (round bar)	$R_{t0.5}/R_m$	(%)	75
yield-to-tensile ratio (round bar)	$R_{p2.0}/R_m$	(%)	96
elongation (round bar)	A_5	(%)	14.3
charpy toughness at -40°C	CVN	(J)	227

Basing on these promising lab results, MRM decided to perform large scale rolling trials in order to be able to deliver X120 plates as soon as there is a need for it.

DEVELOPMENT STRATEGY FOR PLATES WITHIN THE SALZGITTER GROUP

The close cooperation within the Salzgitter Group, beginning with customer's demand via research and development at Salzgitter Mannesmann Forschung to plate production at MRM leads to a product and process design which fulfilles all customer requirements. These successes are only possible by collecting and connecting the know-how of all involved participants within the Salzgitter Group and by bringing it into a straight line from the challenge to the finished product.

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