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THE DEVELOPMENT OF HIGH STRENGTH HEAVY PLATE FOR THE PIPE INDUSTRY USING MODERN EXPERIMENTAL AND NUMERICAL METHODS

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THE DEVELOPMENT OF HIGH STRENGTH HEAVY PLATE FOR THE PIPE INDUSTRY USING MODERN EXPERIMENTAL AND NUMERICAL METHODS

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Abstract
This paper gives an overview on the development chain for high strength heavy plates and line pipes for the Salzgitter subsidiaries Mannesmannröhren Mülheim and Europipe. The complete material flow from steel to plate, pipe and pipe bend as well as all necessary R&D activities are available among the Salzgitter subsidiaries. Development, optimisation and production of X80 plates, line pipes and pipe bends are described. The development status of steel grades X100 and higher at Mannesmann/Europipe is summarized.

1. Introduction

Mannesmannröhren Mülheim, a member of the Salzgitter group, runs a 5.1-meter heavy plate rolling mill which is specialized on the production of plate for pipe. More than 90 percent of its more than 750,000 tons annual plate production is delivered to large diameter pipe mills all over the world. The most important and biggest customer is the German pipe producer Europipe which is a joint venture of the two steel manufacturers Salzgitter and Dillinger Hütte. MRM developed and improves ultra high strength heavy plates mainly for this customer. All important steps of this development take place within companies integrated or at least partly integrated in the Salzgitter group: the steel is produced at Hüttenwerke Krupp Mannesmann (HKM), the plates are rolled at Mannesmannröhren Mülheim (MRM), the pipes are manufactured at Europipe, bends can be manufactured at MRM´s own pipe bending plant. Last but not least the whole research and development for this production chain is performed in cooperation with Salzgitter Mannesmann Forschung (SZMF) which is the development centre of the Salzgitter group.

Since the beginning of the eighties of the 20th century, plates, pipes and pipe bends of steel grade API X80 were developed and produced at Mannesmann and Europipe. Since these days the X80 products were steadily improved for example in terms of toughness and weldability. Today they are daily business for both companies. Figure 1 gives an impression of the produced tonnage of heavy plates to date as well as the number of produced pipe bends in API Grade X80.

In the beginning of the nineties, both partners started to work on the development of API X100 plates and pipes. While X80 today is daily business for both companies, X100 plates and pipes were produced on trial scale up to now. Some 1000 tons of X100 plates and pipes of different dimensions were manufactured so far. In the following chapters the development steps for these high grade steel products are described and some actual production results are presented.

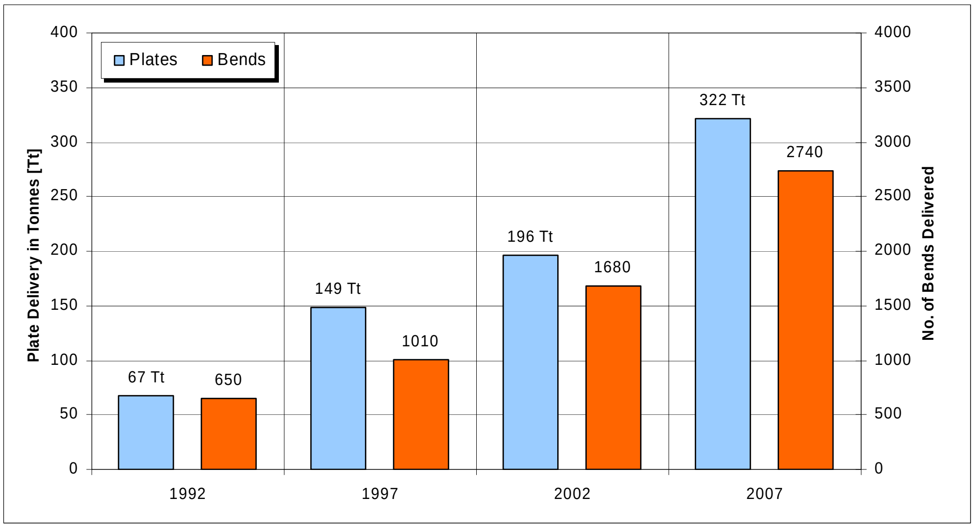

Figure1: Development of X80 production at MRM GmbH

2. From an idea to the finished product

2.1 Preliminary investigations, theory and numerical simulations

The development of microalloyed steels for linepipe applications is a focus of research efforts at the SZMF. A broad database of results of rolling trials has been gathered, ranging up to the X120 strength level. The analysis of these data and of results of heavy plate production forms the basis for process optimisation and development of new processing strategies. This is complemented by numerical tools that are used for alloy design.

Over the past decades, the numerical simulation of phase equilibria and kinetics of phase transformations has developed into a tool that is no longer only of academic interest but has significantly broadened the understanding of processes that occur within steels along the entire industrial process route, from continuous casting of slabs to double-submerged arc welding of large diameter pipes. At the SZMF, these methods have been embraced and are used for the development of high-strength microalloyed steels.

In microalloyed steels, the phase equilibria of the carbonitride precipitates of niobium, vanadium and titanium are of great interest as these precipitates have a strong influence on grain size, recrystallisation, precipitation hardening and the mechanical properties of the product. At the SZMF, the phase equilibria are calculated using Thermo-Calc in combination with the TCFE3 database. It has been shown by microstructure investigations that steels that are alloyed both with niobium and titanium develop precipitates with different sets of chemical composition [1]. One type of precipitates is rich in titanium and nitrogen while the other is rich in niobium and carbon. As has been shown recently, this phase equilibrium can be described in Thermo-Calc by assuming a three-phase miscibility gap between austenite and the two carbonitrides [2]. This makes it possible to calculate the equilibrium temperatures of formation of both carbonitrides. This is shown exemplarily in Figure 2 for a high-strength steel microalloyed with niobium and titanium.

During reheating of the slabs, it is desirable to dissolve a high amount of niobium in the austenite in order to obtain a fine distribution of niobium-rich carbonitrides during thermo-mechanical treatment. This fine distribution of precipitates is responsible for inhibiting recrystallisation of the austenite and makes it possible to reach the low grain sizes required in order to obtain the high strength and toughness required for modern linepipe steels [3]. Reheating below the dissolution temperature leads to coarsening of the carbonitrides which are then less effective in inhibiting recrystallisation. These computed dissolution temperatures of niobium carbonitride are used as guidelines for the selection of reheating temperatures in laboratory-scale rolling trials at the SZMF and production-scale rolling trials at Mannesmannröhren Mülheim.

In addition, the calculation of the phase equilibria shows that the titanium-rich carbonitride forms close to or slightly above the solidus temperature. Formation of titanium-rich carbonitrides during solidification is generally not desirable because particles formed in the

liquid phase can coarsen quickly owing to the high mobility of alloying elements in the liquid phase. This leads to particle sizes of the order of several micrometers which have been reported to impair toughness, especially in the heat-affected zone of linepipe material [4].
As in the case of niobium-carbonitrides, a fine dispersion of titanium carbonitrides is desirable in order to prevent excessive grain coarsening during reheating [5]. In the case of phase transformations close to the solidus temperature of microalloyed steels, equilibrium calculations reflect reality only to a limited extent, since the temperature range of solidification is underestimated in the calculation, because the limited redistribution of alloying elements in the solid is not taken into account.

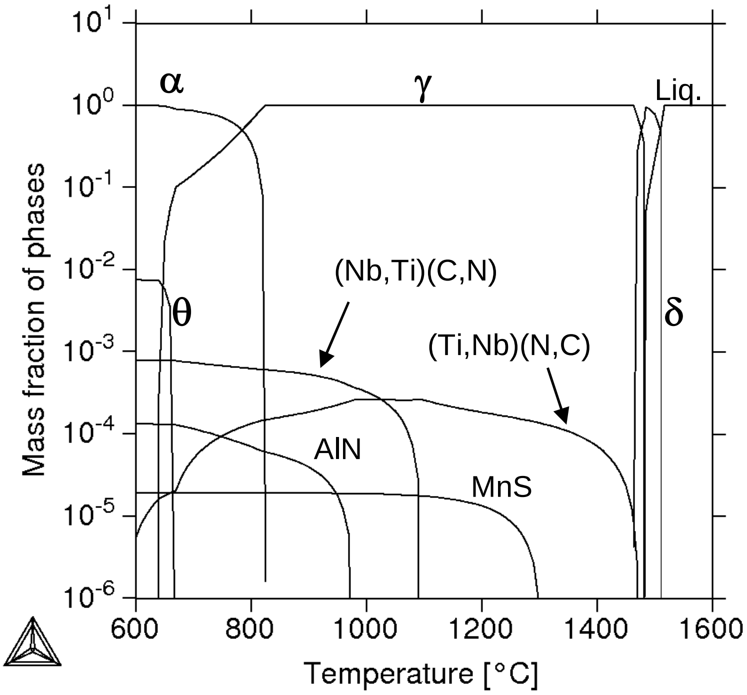

Figure 2: Mass fraction of phases as a function of temperature for a NbTi microalloyed high-strength steel with about 0.09 wt.% carbon, 0.3 wt.% silicon, 1.7 wt.% manganese

More realistic results have been obtained at the SZMF using the Scheil-Gulliver model [6] and DICTRA [7], a software package that allows modelling the kinetics of diffusion-controlled phase transformations. In the former approach, the mobility of alloying elements in the liquid is considered to be infinite, but no redistribution of elements is allowed in solid phases. This, however, constitutes a simplification that leads to larger computed solidification ranges compared to reality. The strength of the Scheil-Gulliver model, however, lies in its ability to handle alloy compositions with a high number of components. DICTRA, on the other hand, takes diffusion in the solid phases into account, which leads to the best results with regard to the solidification range. Handling systems with a large number of components is, however, numerically difficult. Both approaches are currently compared at the SZMF. An example of a result of a calculation using the Scheil-Gulliver model is shown in Figure 3 for a microalloyed steel with about 0.09 wt.% carbon, 0.3 wt.% silicon, 1.7 wt.% manganese, 0.04 wt.% niobium and a titanium content of 0.025 wt.% (a) and 0.012 wt.% (b) with a constant nitrogen content of about 50 ppm. All other elements except titanium were held constant. The arrows indicate the onset of the formation of (Ti,Nb)(N,C) precipitates. It is evident that lowering the titanium content to around 0.012 wt.% leads to formation of (Ti,Nb)(N,C) particles at a temperature where the weight fraction of solid is more than 10% higher than at a titanium level of 0.025%. Bearing in mind that Scheil-Gulliver calculations tend to overestimate the solidification range, it is safe to assume that the weight fraction of solid is even higher than predicted. The tendency to form primary (Ti,Nb)(N,C) particles is therefore significantly reduced by reducing the titanium content of the steel.

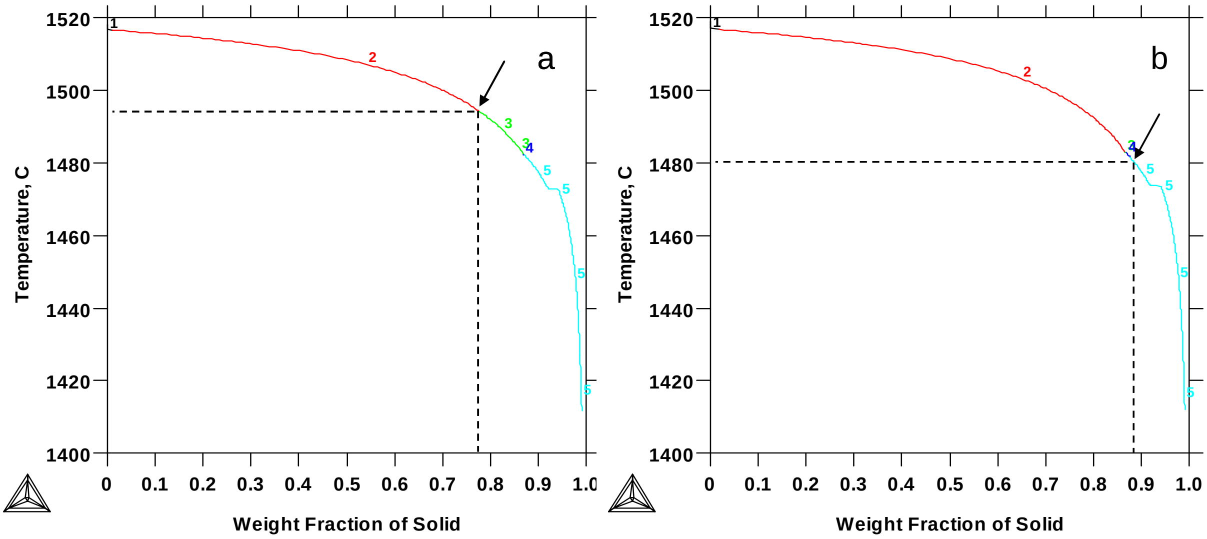

Figure 3: Weight fraction of solid as a function of temperature using the Scheil-Gulliver model

These two examples illustrate the use of numerical methods for alloy design which, in combination with analysis of results from previous rolling trials, form the basis for the selection of appropriate chemical compositions for experimental investigations.

2.2 Experimental Investigations

After appropriate compositions have been defined, vacuum induction heats of up to 300 kg can be cast at the SZMF. These can then be used for laboratory rolling trials on a 2-high reversing rolling stand capable of rolling slabs with a thickness of up to 200 mm. A water cooling unit equipped with four laminar water curtains is used for accelerated cooling, with which cooling rates of up to 50 K/s/inch can be realised. The temperature of the material is monitored between rolling passes and after accelerated cooling using pyrometers and recorded with an electronic data acquisition system. This combination of laboratory rolling in combination with accelerated cooling is general practice at SZMF in the case of alloy and process design for high strength steels and has been successfully employed up to a wall thickness of 40 mm for the grade X80, 25 mm for X100 and 20 mm for X120. Alternatively, samples taken directly from continuous cast slab material from the Hüttenwerke Krupp Mannesmann can be used in order to test different rolling strategies of interest for production of high-strength heavy plates at MRM. This is generally followed by testing of the mechanical properties, microstructure investigations, both with light-optical microscopy and electron microscopy, and may include submerged arc welding trials with up to 5 wires, as employed in the production of large diameter pipes at EUROPIPE.

In 2007, a new rolling stand has been installed at the SZMF that is capable of processing slab material of up to 400 mm thickness. A schematic drawing of the equipment is shown in Figure 4. This investment significantly enhances the capabilities of the SZMF to investigate the benefits of high slab thickness of above the standard gauge of 260 mm for the production of linepipe steels and allows the use of rolling parameters that are even closer to production. To the knowledge of the authors, a rolling stand of this size is unique for an industrial research centre.

In the following section, an example of a laboratory investigation carried out at the SZMF with the aim to develop processing strategies for X80 is given.

Increasingly stringent requirements regarding the weldability of linepipe steels have driven the development of steels with reduced alloy content. That the mechanical properties required of high strength grades can still be fulfilled with these compositions has been made possible through continuous optimisation of the thermo-mechanical controlled process. Two alloying strategies that were investigated at the SZMF are shown in Table 1. These differ in the use of the elements vanadium and chromium, on the one hand, or copper and nickel, on the other hand. The benefit of identifying different alloying strategies with which comparable mechanical properties can be achieved lies in a greater flexibility to react to price fluctuations on the raw material market.

Laboratory rolling trials were carried out with accelerated cooling, in which the wall thickness was 20 mm, the final rolling temperature was above A_3 and the cooling stop temperature was varied between 400°C and 650°C with cooling rates above 10 K/s. The microstructure that is typically obtained using this procedure consists predominantly of bainite with minor volume fractions of ferrite and martensite, as shown exemplarily in the light-optical micrograph in Figure 5.

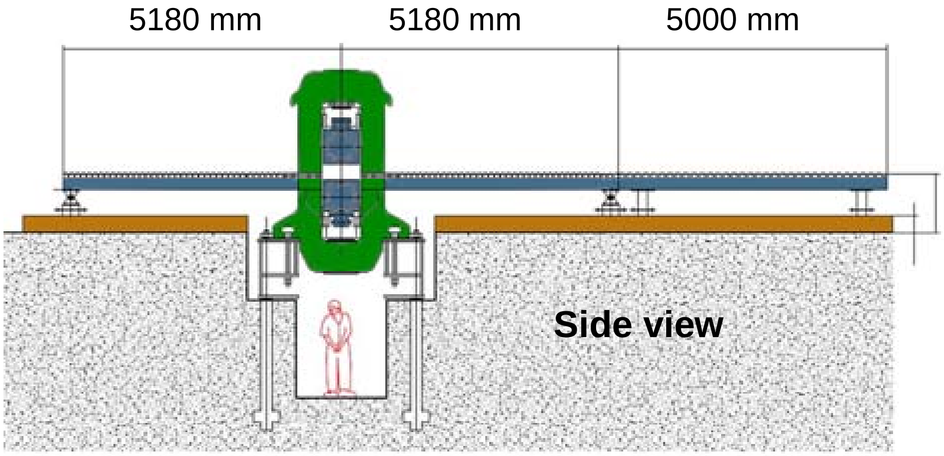

Figure 4: Schematic drawing of the rolling stand installed in 2007 at the SZMF.

	C	Si	Mn	Nb	Ti	others	CE(IIW)
Type 1	0.06	0.30	1.90	0.06	<0.025	V, Cr	0.43
Type 2	0.06	0.30	1.90	0.06	<0.025	Cu, Ni	0.44

Table 1: Possible alloying concepts for the grade X80 and the resulting carbon equivalents

According to the API specification 5L [8], a minimum yield strength of 552 MPa and an ultimate tensile strength of 621 MPa are required for this grade in transverse direction. The results of round bar transverse tensile tests are presented in Figure 6. The results show that the requirements can be fulfilled with both alloying concepts and that in both cases a decrease of the cooling stop temperature leads to an increase in the yield strength but also to an increase in the Y/T ratio. Charpy impact tests were carried out between -20°C and -80°C on V-notch specimens and showed that the mean impact energy remained above 200 J in all cases down to a temperature of -60°C, i.e. sufficient toughness was achieved with both alloying concepts.

The laboratory-scale rolling trials showed that the grade X80 can be safely produced with both alloying concepts with a carbon equivalent of below 0.45, thus ensuring improved weldability.

The microstructures of bainitic high strength steels can be characterised by light optical microscopy only to a limited extent because of the small size of the features. Especially the effect of processing parameters on the bainite morphology and the correlation with the mechanical properties is of great interest to the heavy plate producer. Electron backscatter diffraction (EBSD) is a method that is used at the SZMF in order to obtain a better understanding of the effects of rolling and cooling conditions on the mechanical properties of bainitic steels. An example of an EBSD mapping of the CuNi sample shown in Figure 5 is presented in Figure 7.

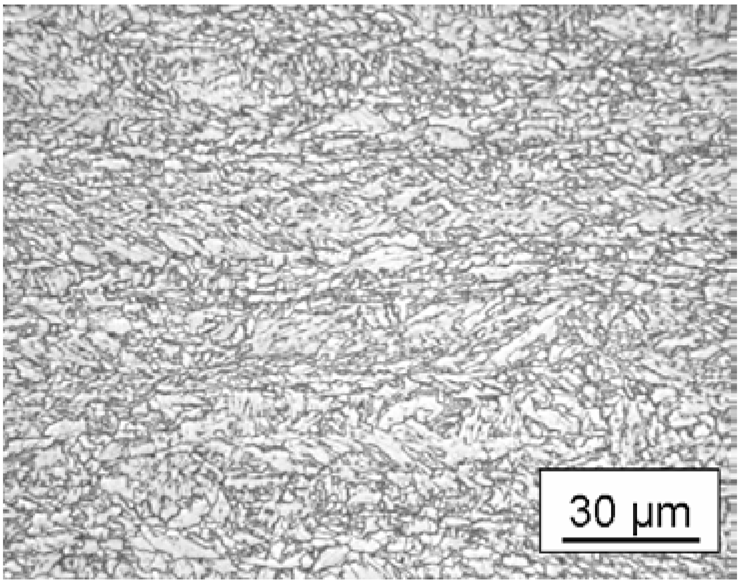

Figure 5: Typical microstructure of a CuNi sample with an intermediate cooling stop temperature at a magnification of 500:1

Each colour in this image corresponds to a certain crystal orientation. Misorientation relationships between neighbouring grains and orientation gradients within grains can be measured with this method. Small angle grain boundaries with a misorientation below 15° are coloured in grey and large angle grain boundaries with a minimum misorientation of 15° are black. Such an image can be analysed quantitatively and the misorientation distribution, the local misorientation or the size of domains or cells that are bordered by large angle grain boundaries can be obtained. EBSD measurements were carried out on samples of the CuNi and VCr variants with different cooling stop temperatures. It was found that the mean cell size, i.e. the size of domains bordered by large angle grain boundaries (black in Figure 7) with a misorientation of at least 18° with regard to neighbouring regions, varied between 2.2 µm in the case of a low cooling stop temperature and between 3.5 and 4.9 µm at high cooling stop temperatures. The standard deviation of the measured size distributions was about 10% of the mean cell size. This was found to correlate with the uniform elongation of the material in transverse direction, see Figure 8. This result is significant for the production of high strength grades because it bridges the gap in the understanding between the processing parameters and resulting mechanical properties.

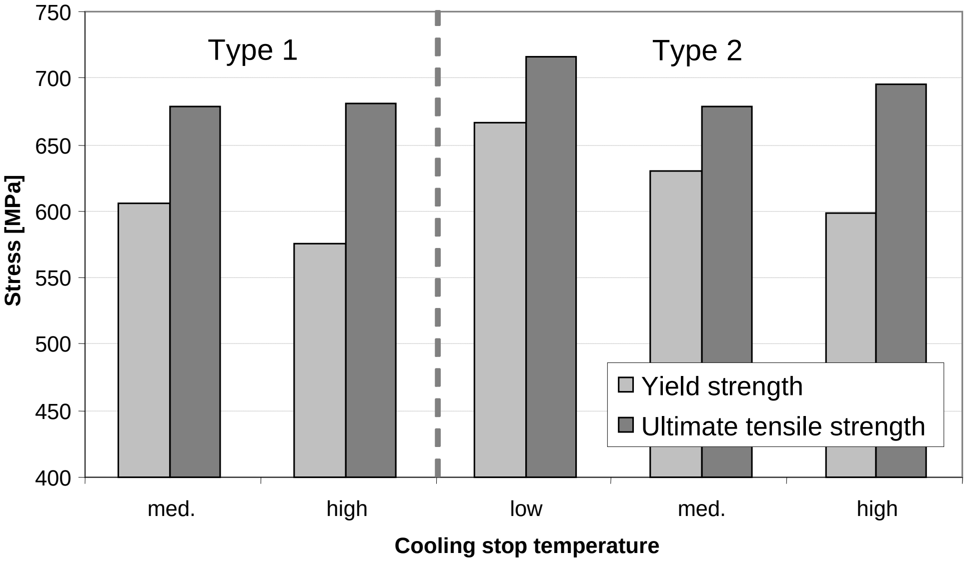

Figure 6: Results of round bar tensile tests for the plates produced in the laboratory rolling trials

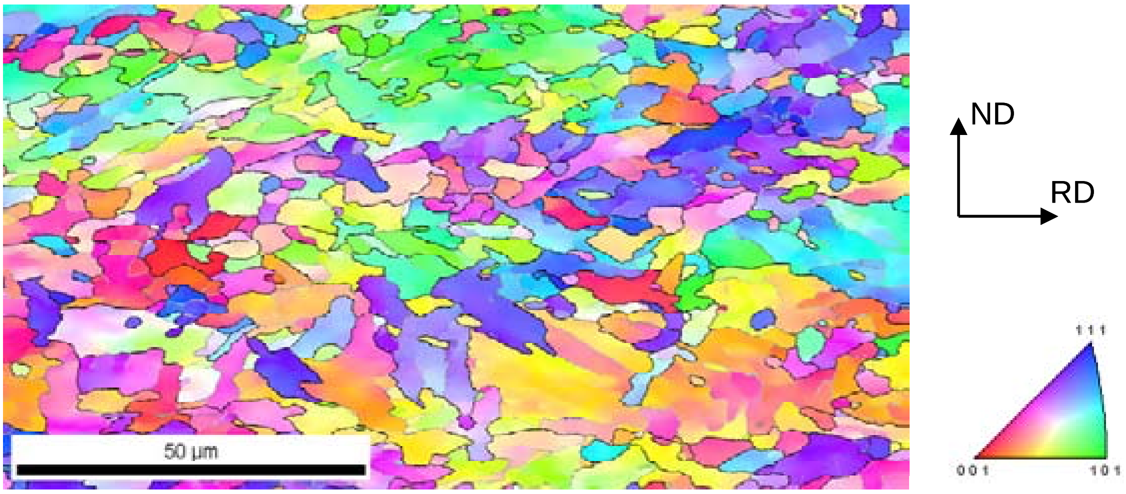

Figure 7: Inverse pole figure obtained from an EBSD mapping of the CuNi sample

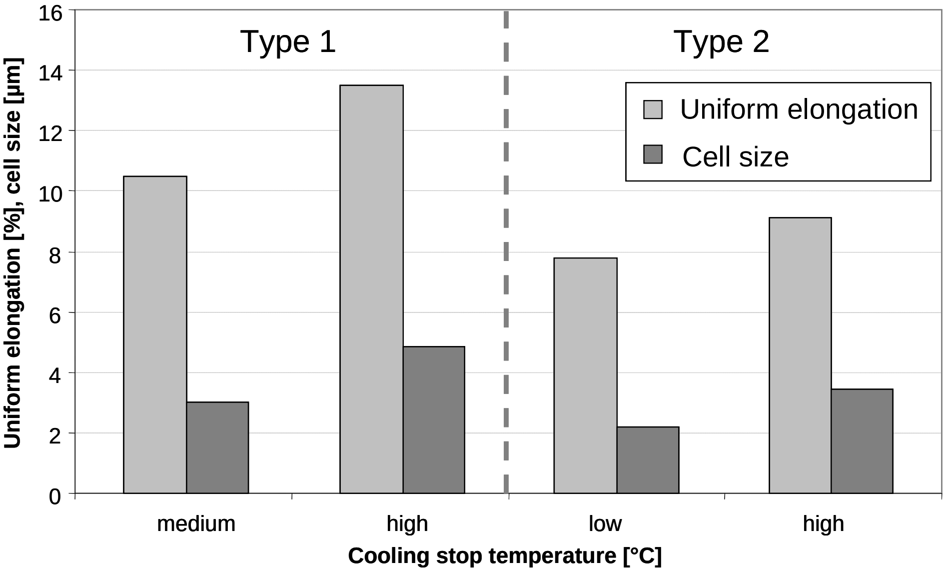

Figure 8: Relationship between cooling stop temperature, uniform elongation and the cell size

2.3 High strength heavy plate production

Once an optimum combination of mechanical properties is obtained in the laboratory rolling trials, the processing parameters can then be used as a basis for trial production at the heavy plate mill of MRM. This was done for example with the two afore mentioned alloying concepts which both were utilized during a large scale rolling campaign for heavy plate for pipe application in steel grade X80. Table 2 gives an overview of the required mechanical properties for these plates.

	SMYS MPa	**UMTS MPa**	**CVN* J**	**BDWTT* %**	**Elong. %**	**Y/T**
transverse	555	625	115/150	75/85	18	0,90

Table 2: Required mechanical properties of X80, *****design temperature for CVN and BDWTT 0°C

After successful large scale rolling trials the production of 17T tons of X80 plate (20.5 mm wall thickness and 3730 mm width) was performed with alloying concepts type I and type II.

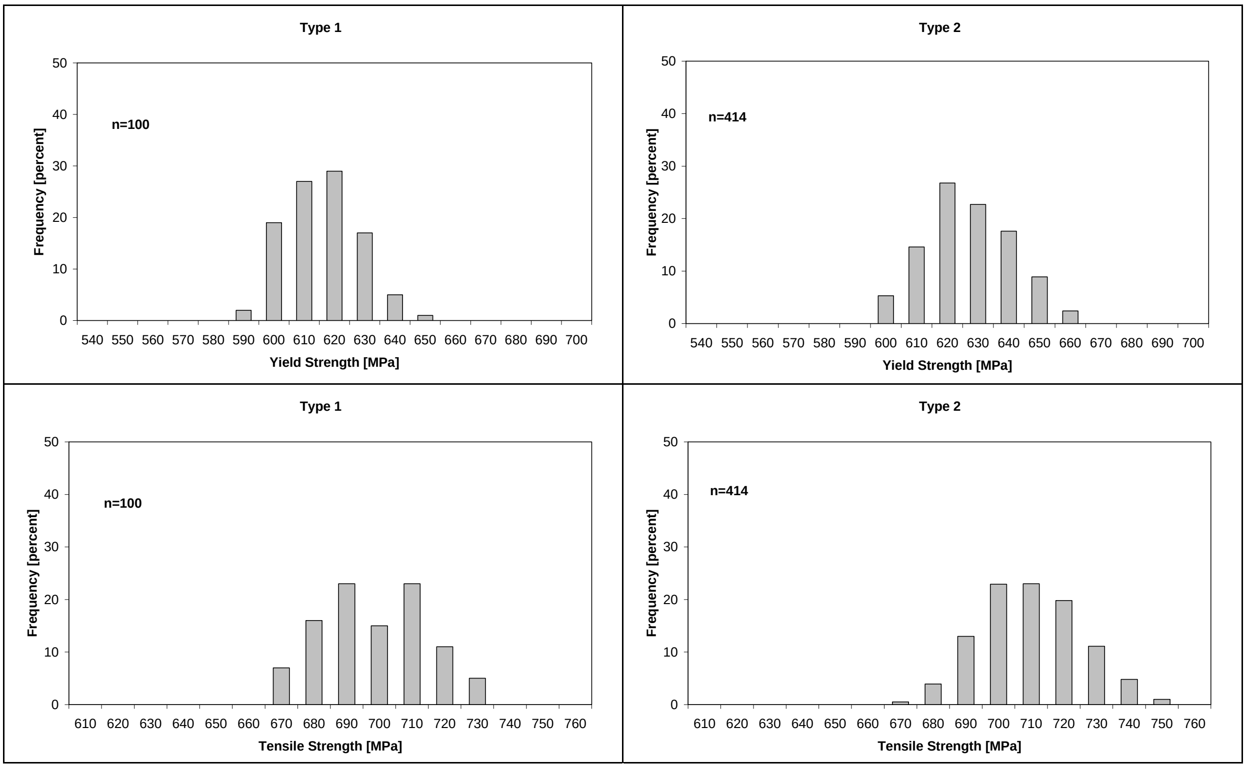

Figure 9: Strength properties for alloying concept type I and type II

Figure 9 gives a statistical overview of the achieved results for tensile and yield strength properties for both alloying concepts during large scale production. Independent of the applied alloying concept, both statistical distributions are well above the required minimum for yield and tensile strength properties.

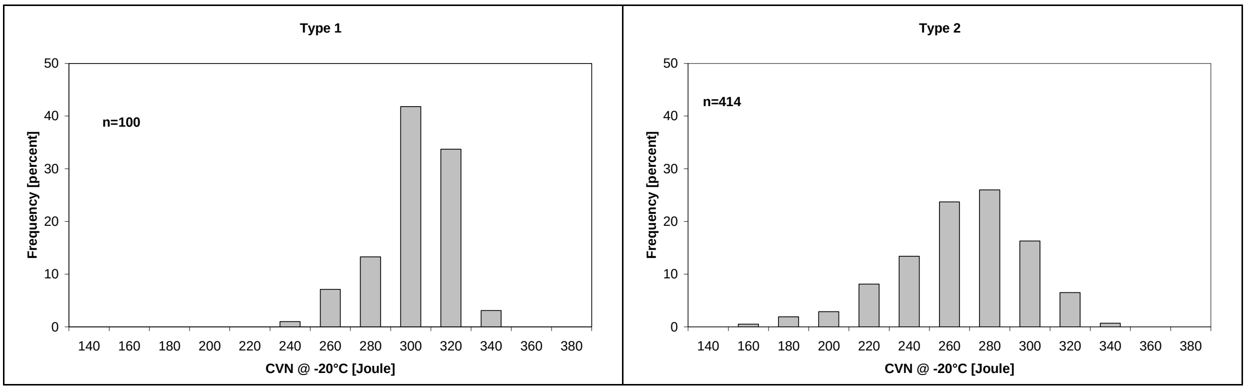

Figure 10: Toughness properties for alloying concept type I and type II

Figure 10 shows the achieved results for the toughness properties at a testing temperature of -20°C for both alloying concepts. As can be seen from the bar chart the obtained results are well above the desired minimum values. The Batelle drop weight tear properties were tested at -10°C. The obtained results are also well above the desired minimum values.

Figure 11 shows the obtained stress strain curve and microstructure for the production. The microstructure is bainitic, leading to a round-house shape of the stress/strain curve.

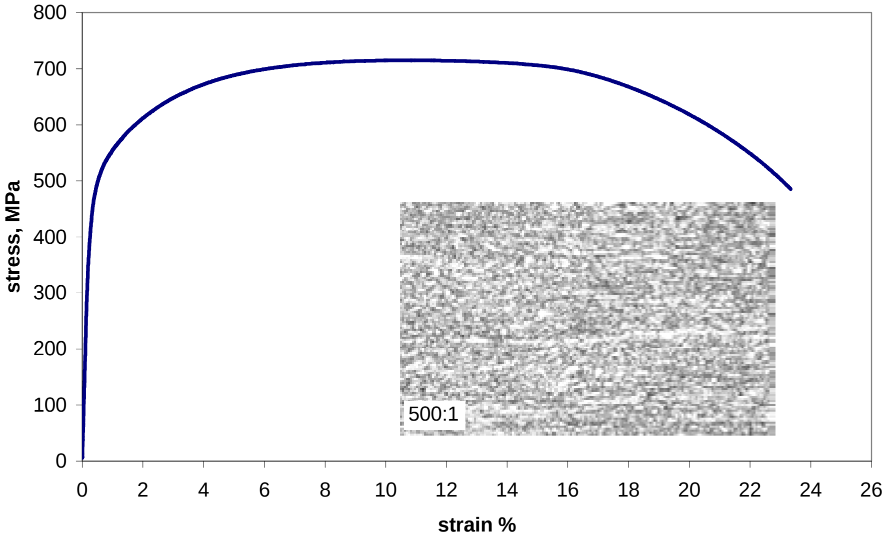

Figure 11: Stress-strain curve and achieved microstructure

The statistical distribution of the mechanical properties indicates that both alloying concepts yield full compliance with the requirements. Both concepts offer the same excellent weldability due to a low alloying content. This gives the flexibility to react on varying alloying costs for medium wall thickness X80 plate in order to keep the plate costs for the customer as stable as possible.

2.4 High strength SAWL pipe production

The final goal of the above described development on plate is the production of longitudinally welded X80 large diameter line pipe with consistent high quality and high productivity. During the last two decades, EUROPIPE has carried out extensive work in cooperation with their plate suppliers to develop high-strength steels in grades X80 and above to assist customers in their endeavour to reduce weight and pipe laying costs.

Since 1984, longitudinal welded X80 pipes were applied to several pipeline projects in Europe and North America. The total quantity delivered since 1984 amounts to 1000 km for the projects listed in Table 3.

Year	Project	Main Pipe Geometry	Pipeline Length
1984	Megal II	44“ x 13.6 mm	3.2 km
1985	CSSR	56“ x 15.4 mm	1.5 km
1991/92	Ruhrgas	48“ x 18.3 mm 48“ x 19.4 mm	259 km
2001/03	CNRL	24“ x 25.4 mm	12.7 km
2003	Murray	20“ x 20.6 mm	2.4 km
2004	Stadtwerke Münster	56“ x 20.5 mm	1.6 km
2004/05	SnamReteGas	48“ x 16.1 mm	10 km
2001-2007	National Grid (Transco)	48“ x 14.3 mm 48“ x 15.9 mm 48“ x 22.9 mm	690 km

Table 3: Projects with line pipes manufactured in Grade X80

As the requirements especially regarding weldability and toughness were incrementally increased during this period, it was necessary to modify the plate rolling parameters and the alloying design accordingly. The most effective measure to improve both weldability and toughness is the reduction of Carbon content. As the strength requirements remained basically unchanged, additional alloying became mandatory in order to maintain the hardenability and the strengthening parameters.

The measured tensile and impact energy values conformed to the specification requirements in all cases. The standard deviation for the yield and tensile strength values is low. The impact energies measured on Charpy V-notch impact specimens at 0°C is very high. The 85% shear transition temperatures determined in the Batelle drop weight tear (BDWT) tests are far below 0°C.

Mechanical properties of recent X80 production are shown in the Figures 12 and 13. The pipe dimension was 48”O.D. with a wall thickness of 22.9 mm. All results of the tensile and impact tests performed were consistently within the specification range for grade X80. The standard deviation was 16 MPa for the yield strength values and 15 MPa for the tensile strength values.
The average value of 3 CVN specimens was minimum 190 J with a mean value of 320 J for base material (Figure 13, left side). The excellent toughness in the base material is confirmed by the results of the BDWT- tests as depicted on the right side of Figure 13.

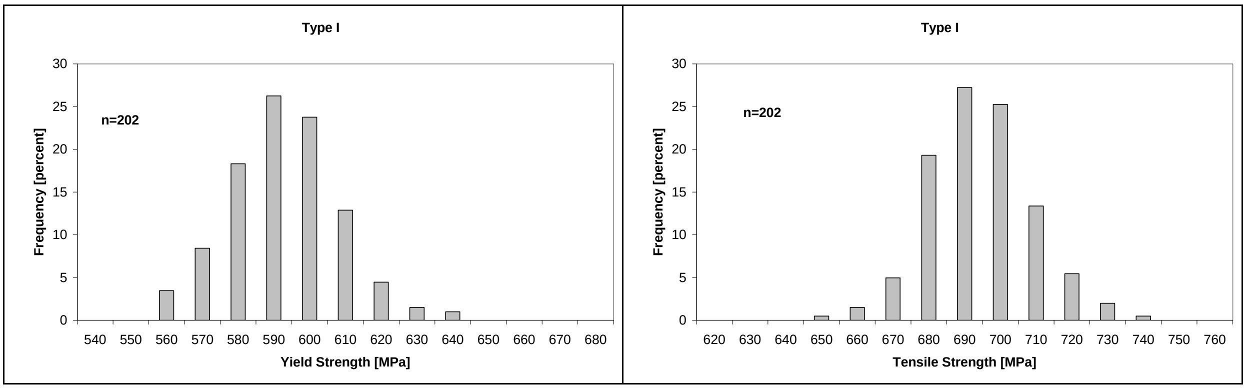

Figure 12: Strength properties of X80 Pipes (48”O.D. x 22.9 mm W.T.)

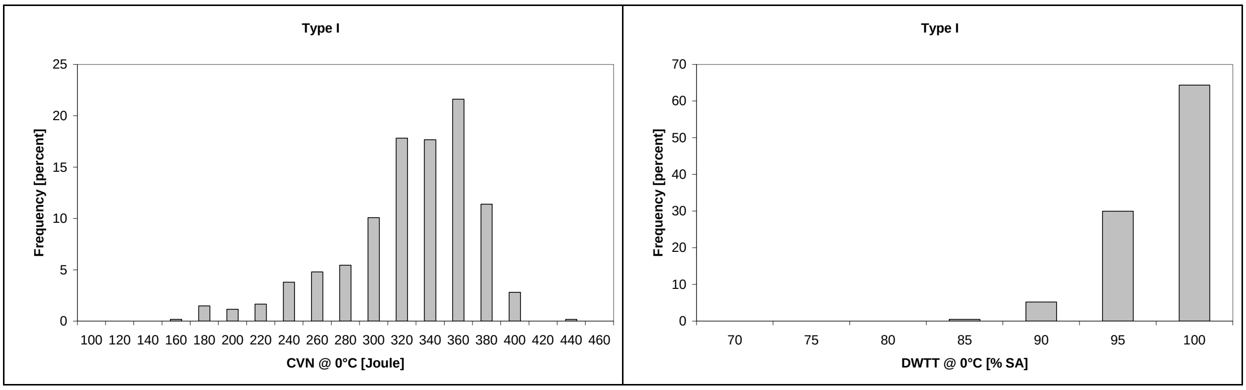

Figure 13: CVN and DWT test results of X80 Pipes (48”O.D. x 22.9 mm W.T.)

In another production run, X80 line pipe was manufactured based on alloying type II according to identical specification requirements. The results on pipe were found to stay within the same range fully complying with the requirements irrespective of the chemical composition.

2.5 High strength induction pipe bend production

As can be gathered from Figure 1, the production of hot induction bends in material grade X80 increased comparably to X80 plate production at MRM over the last 15 years.

Even for high strength requirements it is possible to manufacture hot induction bends from SAW large diameter pipes, produced from Thermomechanically Controlled Rolling Process TMCP plates. Nevertheless important facts have to be considered for the design of the high strength pre-material regarding the chemical analysis and its dimension.
Induction bending is a free forming process where a pipe is pushed through an induction coil. The pipe is clamped at its front end and forced to follow the radius of the bending arm (Figure 14). The deformation is limited to the narrow zone heated by the induction coil (Figure 15).

To avoid high ovalisation in the bend body, the width of the heated zone must be limited and is typically 2x wall thickness of the pipe to be bent. For this purpose, the formed material is cooled by water spray immediately behind the induction ring. Depending on the wall thickness and radius to be bent, different bending parameters have to be respected and controlled in a narrow range.

Figure 14: Hot induction bending of 48" line pipe at Mannesmann Bending Plant

Figure 15: Detailed view on induction coil and heated zone during bending

Due to the process related heating of the material during forming to temperatures above $A_{c3,}$ the TMCP microstructure receives a short-time austenitisation followed by water quenching. Figures 16 and 17 show the transformation of the microstructure of X80 material before and after hot induction bending. To guarantee high strength properties also after bending, the chemical composition has to be designed for sufficient hardenability. Therefore alloying elements as Cr, Cu and Mo must be added to the X80 line pipe analysis. The carbon equivalent (CE_{IIW}) for mother pipes suitable for induction bending is typically 0.03 to 0.04 higher than for the line pipe material.

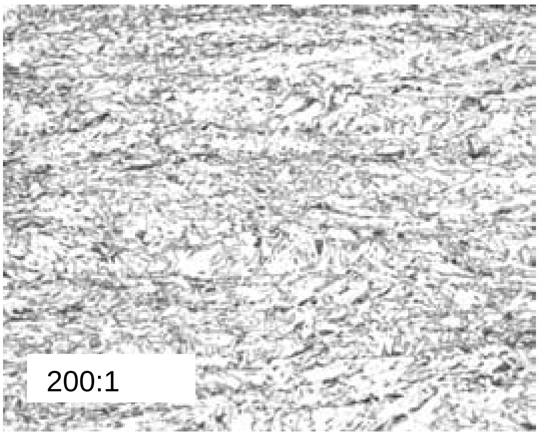

Figure 16: Microstructure of TMCP X80 mother pipe before bending

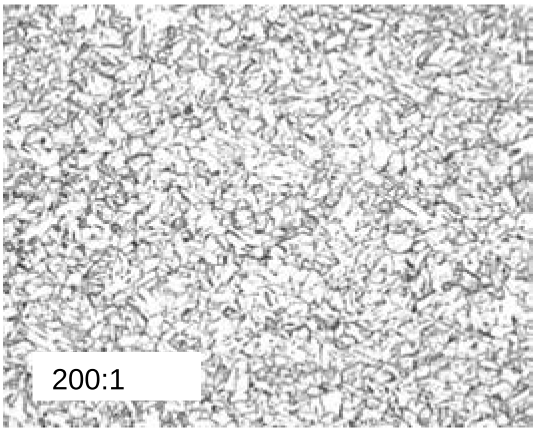

Figure 17: Microstructure of X80 hot induction bend

The bending of SAW large diameter pipes with a wall thickness up to 30 mm is always followed by a full body temper heat treatment at MRM's bending plant. For bends with wall thickness above 30 mm MRM recommends a full body QT heat treatment after bending. Average results of 200 test bends measuring 48" x 19.5 and 28.5 mm wt. with a radius of 3D in material grade X80 are summarized in Table 4 for yield and tensile strength, elongation and toughness properties.

	Specified Values	**Production Results** **average values from 200 Test Bends**
Yield Strength	555-675 MPa	571 MPa
Tensile Strength	625 MPa min	717 MPa
A_5-Strain	18 % min	20,5 %
Y/T-Ratio	0.90 max	0.80
Charpy Base Material	55 J @ ±0°C	283 J
Charpy Weld Metal	55 J @ ±0°C	157 J

Table 4: Mechanical Results of X80 Induction Bends

MRM is able to design the necessary pre-material which is suitable for induction bending in view of the required dimension and the adequate chemical composition for mother plate and pipe production, respectively. Actually the development of hot induction bends is focused on material grade X100. Consequently, high strength hot induction bends from TMCP material can be fabricated by MRM according to the customers needs.

2.6 Structural behaviour

Apart from the classical mechanical tests of the base material and the weld seam that may range from tensile tests to CTOD tests, the mechanical properties of the component can be evaluated at the SZMF. Facilities are available to carry out burst tests, collapse tests, ring expansion tests or fatigue tests. The results are of great value to the pipe producer and the designer, especially in the case of high strength steel grades that are currently developed in order to study the failure behaviour of pipes under realistic loading conditions and correlate it with small-scale test results. In the following, a brief overview of the experiences gained at the SZMF with regard to the relationship between tensile test results and tests on the component is given.

The relationship between the yield strength $R_{t0.5}$ in transverse direction measured in tensile tests of round bar and flattened rectangular specimens and the yield strength obtained in ring expansion tests is shown in Figure 18 for grades up to X80. This plot shows that the agreement between the yield strength obtained in tensile tests of round bar specimens and ring expansion tests is significantly better than for flattened rectangular specimens.

It has been shown that this effect is related to the flattening of the test specimen and the extent varies with the D/t ratio and strength level [9,10]. However, the equivalent stress at 0.5% total elongation obtained in burst tests does not correspond well for high strength grades with the yield strength $R_{t0.5}$ measured in tensile tests in transverse direction. The maximum equivalent stress in the burst test, on the other hand, is reflected well by the uniaxial tensile strength.

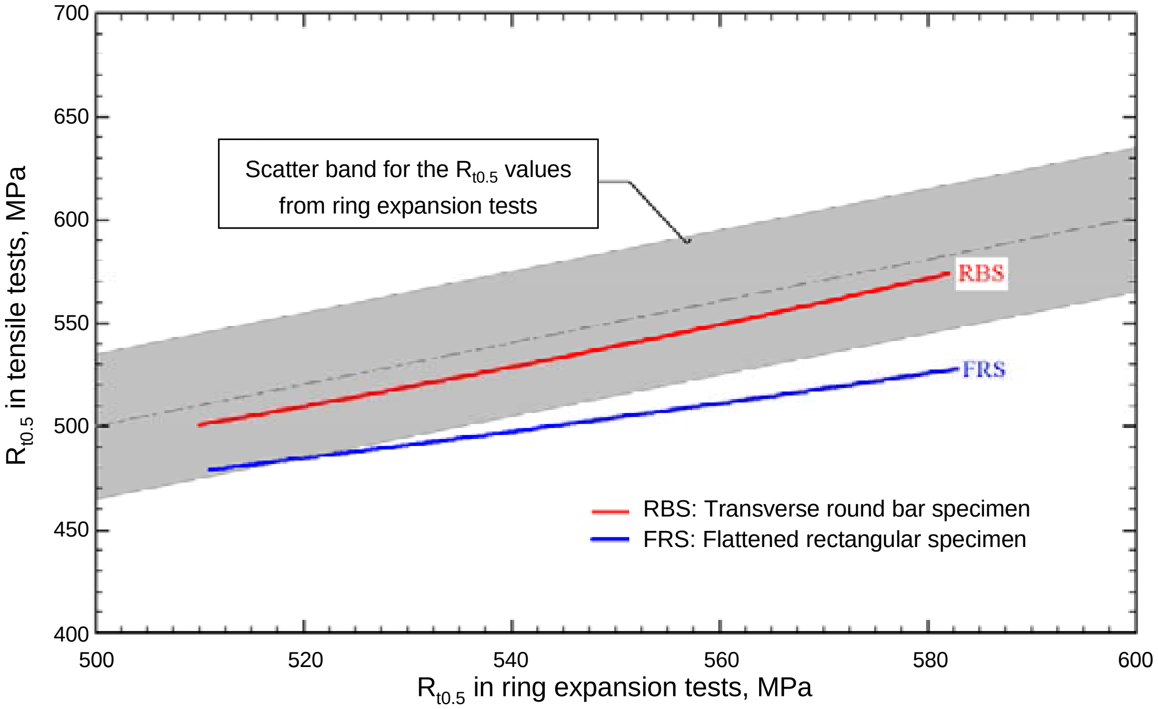

Figure 18: Relationship between the yield strength $R_{t0.5}$ measured in tensile tests in transverse direction and ring expansion tests

3. Development of plates of grade X100 and above

Since 1995 Mannesmann/Salzgitter performed several programs for research and development of heavy plates in steel grade X100. It became obvious that the production window for these high strength steel plates is very narrow [11]. A close and accurate coordination between steel production, rolling and cooling strategy is of great importance for a reproducible performance in terms of mechanical properties. Already in the status of specifying the plate requirements it is necessary to take the specialities of ultra high strength steels into consideration. This is for example the increasing Y/T-ratio and the decreasing strain level with increasing strength. Both tendencies are compensated as much as possible by a suitable process design. Nevertheless, a simple extrapolation of the requirements of conventional strength classes as X70 to the level of X100 is not possible just like that.

In 2003, MRM received an order from Europipe to deliver 300 meters of plate in the dimension of 12,000 mm x 3,742 mm x 18.5 mm for a X100 pipe project. Based on earlier R&D results a CMnVNbTi steel with CuNiMo edition was designed (Table 5). Because of the challenging requirements in terms of Charpy toughness and weldability, a moderate carbon content of 0,06 % was chosen. The process design for this order consisted of a two phase rolling schedule an accelerated water cooling from above A_3-temperature to a cooling stop temperature well below 400°C. The cooling rate was in a medium range. With these cooling parameters a bainitic microstructure was produced which is not too sensitive to the heat input during the later welding of the plate/pipe. Thus, a possible softening effect in the heat affected zone close to the weld seam of the later pipe could be avoided.

C	Si	Mn	Nb	Ti	N	Others	CE(IIW)	Pcm
0,06	0,30	1,90	0,04	0,02	0,004	V, Cu, Ni, Mo	0,48	0,21

Table 5: Chemical analysis of X100 plate for pipe

The achieved mechanical properties of the plates as well as those of the pipes produced of these plates are given in Table 6. All customer requirements were fulfilled.

	Requirement Plate	Property Plate	Property Pipe
Yield Strength	≥ 710 MPa	ø 747 MPa	ø 741 MPa
Tensile Strength	≥ 760 MPa	ø 797 MPa	ø 854 MPa
Charpy	180 J @ - 30°	ø 251J	ø 260 J
DWTT-SAF	75 % @ - 20°	ø 91 %	ø 93 %

Table 6: Required and achieved properties of X100 plate/pipe production in 2003

In 2006 another X100 project was realized for a British pipe customer. Europipe ordered 250 tons of X100 plate with 20 mm wall thickness. A CMnNbTi-steel was used. Special attention was directed to high strain and Charpy values as this was specified in the product specification of the pipe user (strain based design). All plate requirements were fulfilled (Table 7).

	Yield Strength	Tensile Strength	2“-Strain	Y/T - ratio	Charpy	DWTT-SAF
Requirement plate	≥ 700 MPa	≥ 758 MPa	≥ 24 %	≤ 94 %	≥ 130 J (-40°)	≥ 75 % (-20°)
Average value plate	761 MPa	827 MPa	31 %	92 %	270 J (-40°)	83 % (-20°)

Table 7: Required and achieved properties of X100 plate production in 2006

While the first pilot sections of X100 pipes are incorporated into conventional pipelines, Mannesmannröhren Mülheim already thinks about the next step: X120. The first development step for the realisation of X120 plate for pipe was already done on the laboratory scale. With lab heats of CMnNbVTi-steels with an addition of Boron plates in strength level API X120 were rolled on the lab rolling stand [12]. With these promising results, MRM is well prepared for the possible customer requirements in terms of ultra high strength plates.

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