

Improvement of mechanical properties of heavy plates for high strength linepipe application i.e. in arctic regions

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IMPROVEMENT OF MECHANICAL PROPERTIES OF HEAVY PLATES FOR HIGH STRENGTH LINEPIPE APPLICATION I.E. IN ARCTIC REGIONS

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ABSTRACT

This paper gives an overview on the development of high strength plates for line pipe application at Salzgitter Mannesmann Grobblech. From comparably thin X80 plates with no or medium DWTT requirements to recent requirements for approx. 28 mm thick X80 plates with requirements of 75/85 % shear area fraction at -30° C and more than 250 J Charpy energy at -40° C the development work and the results of the last five years are described.

Even for heavy plates of steel grade X100 the requirements for strain and toughness continue to rise. The latest development of grade X100 at SMGB is presented; however, it is not limited to only heavy plates. Since SMGB runs a pipe bending mill, the whole chain from X100 plates to X100 hot induction pipe bends was used to produce X100 pipe bends for the first time. First results in terms of properties and burst test behaviour from X100 plates to X100 pipe bends are presented.

KEYWORDS

Heavy plate, high strength, X100, X80, linepipe, Salzgitter Mannesmann Grobblech, arctic application, bainite, inductive pipe bends, burst test

INTRODUCTION

Salzgitter Mannesmann Grobblech (SMGB), a member of the German Salzgitter Group, runs a 5.1-meter heavy plate rolling mill (figure 1). This heavy plate mill is specialised on the production of plate for large diameter line pipe. The annual production of approx. 800,000 tons is delivered to SAWL pipe mills all over the world. Since these customers traditionally have to be demanding in terms of mechanical properties, weldability, surface quality and last but not least cost, nearly 100 % of the plate produced by SMGB are thermomechanically rolled (TM) and/or accelerated cooled (ACC).

The biggest customer of SMGB is the German pipe producer EUROPIPE which is a 50 % subsidiary of Salzgitter. All important steps of the material development take place in companies integrated or partly integrated in the Salzgitter group: the steel is produced at Hüttenwerke Krupp Mannesmann (HKM), the plates are rolled at SMGB, the pipes are produced i.e. at Europipe and pipe bends can be manufactured at the SMGB pipe bending plant. The whole research and development for this production chain is performed in cooperation with Salzgitter Mannesmann Forschung (SZMF) which is the research centre of the Salzgitter group.

Fig. 1: 5.1-meter heavy plate rolling mill

1. DEVELOPMENT OF HIGH STRENGTH PLATE AT SALZGITTER MANNESMANN

1.1 PLATES IN STEEL GRADE API X100

The development of heavy plates for line pipe application in grade X100 at SMGB was started in 1995. After several laboratory trials first industrial production of X100 plates was performed with a plate thickness t=19.1 mm **[1]**. For this very first trial lot, a comparably high alloying content was used (Carbon equivalent CE_{IIW}=0.49) in order to reach an appropriate strength level with a TMCP rolling schedule with subsequent moderate accelerated cooling (ACC). In the following years, large scale trials were performed to determine the optimum combination of alloying content and cooling conditions **[2]**. Welded pipes made of plates with a comparably high carbon equivalent can exhibit local areas with reduced heat affected zone (HAZ) toughness. On the other hand, plates with a very lean alloying concept need an extreme cooling rate during accelerated cooling. This makes the microstructure more sensitive to softening caused by the heat input beside the weld seam of the later pipe. Hence, a carefully chosen combination of alloying system, deformation ratio per rolling phase and accelerated cooling conditions is necessary to achieve the required mechanical properties and an excellent weldability.

In the last 15 years SMGB has produced a number of different X100 lots in a wide range of widths, thicknesses and requirements. Fig. 2 gives an overview on the X100 plate geometries produced at SMGB so far.

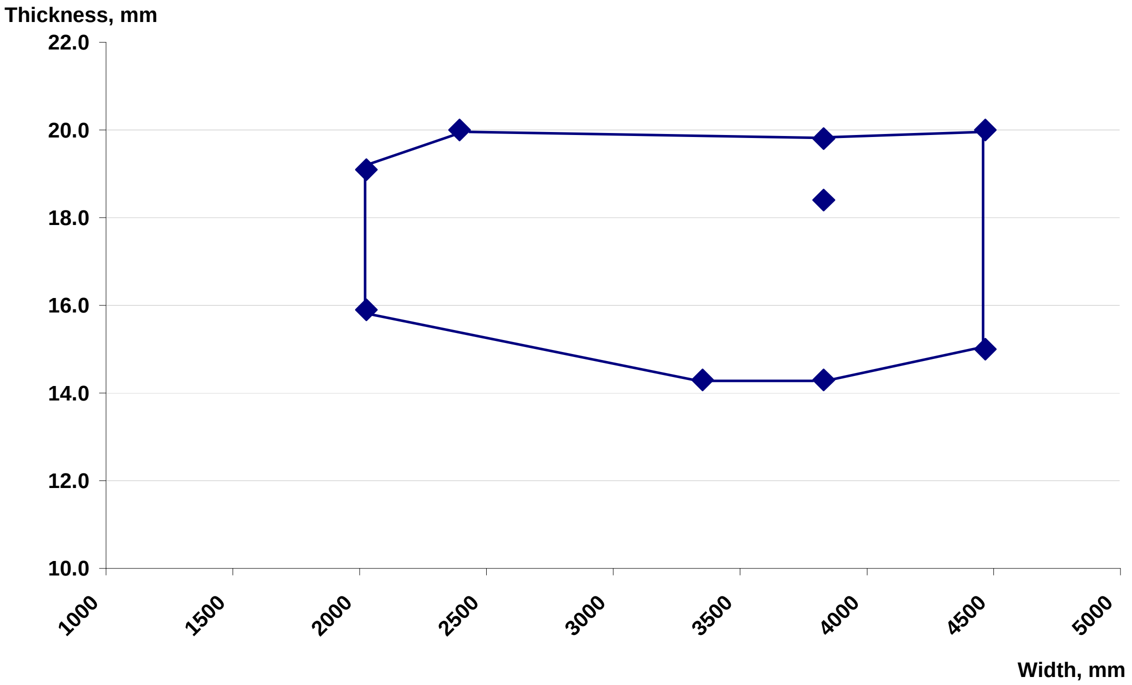

Fig.2: Overview on geometries of X100 plates produced at SMGB since 1995

1.2 PLATES IN STEEL GRADE API X80

The commercial manufacturing of X80 plates at SMGB´s 5.1m rolling mill began in the early 1980s. This first X80 was called “GRS 550” which stood for “Grossrohrsonderstahl 550” (German for Large Diameter Pipe Special Steel 550). The world’s first X80 pipeline was equipped with pipes made from these X80 plates by SMGB. While this was a trial lot of 3.2 km pipeline length, the next step was the 250 km long natural gas pipeline from Werne to Schluechtern in Germany for which the plates were also produced at the SMGB heavy plate mill **[3]**. Since then, SMGB has produced more than 380,000 metric tons of X80 plates for various customers and according to European, United States, Canadian and Russian standards (figure 3).

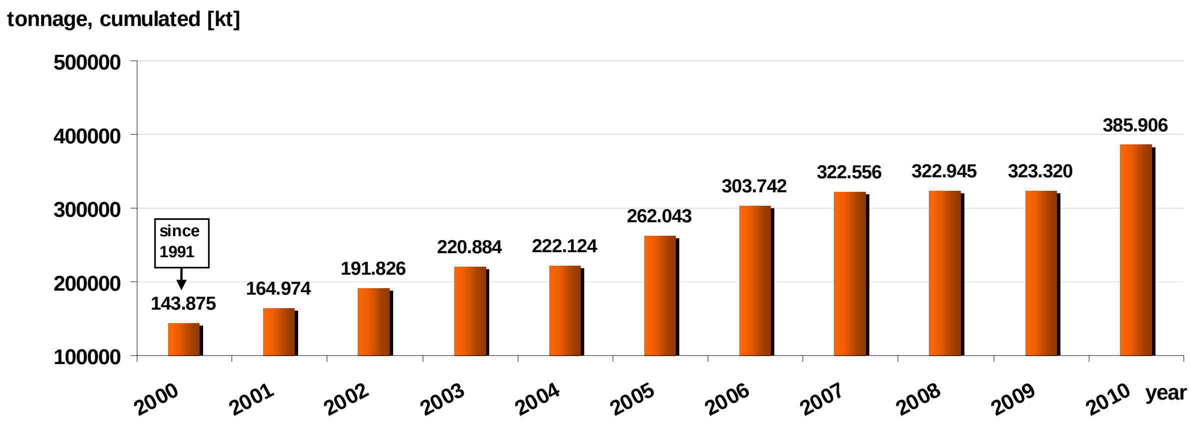

Fig. 3: Cumulated tonnage of X80 plates from 2000 to 2010 produced by SMGB

The plate thickness range varied from 11 mm to 40 mm, while the maximum width was 4470 mm which corresponds to a 56 inch pipe (see figure 4).

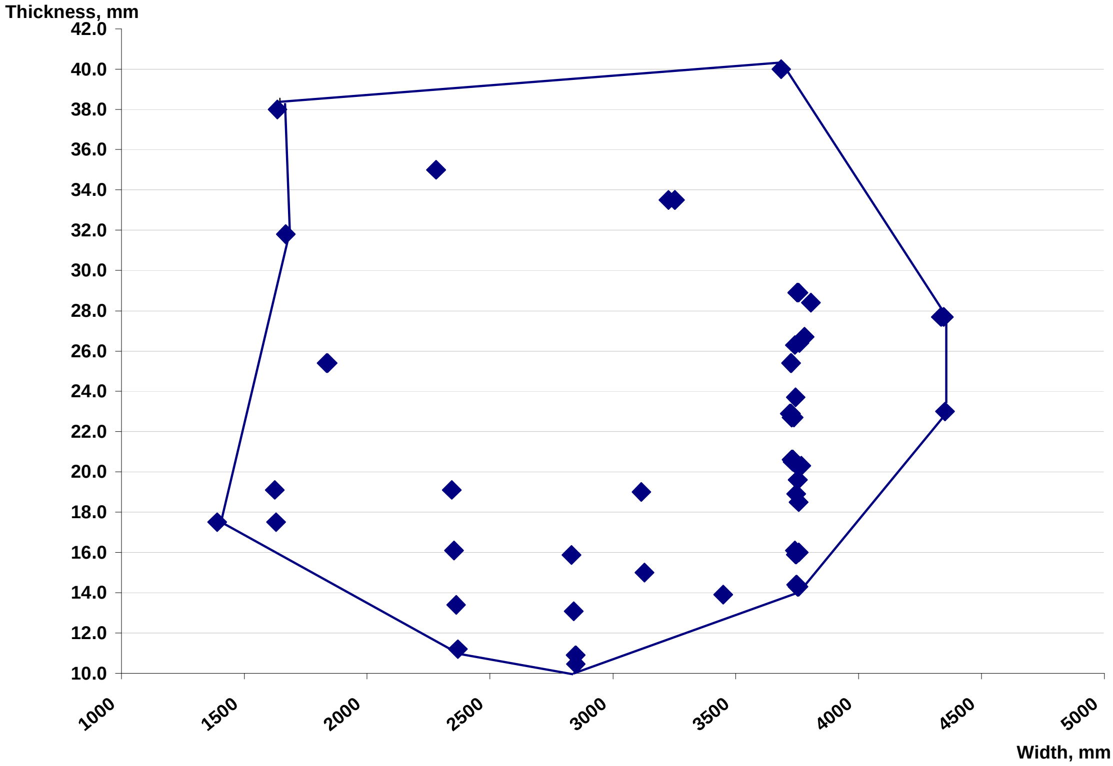

Fig.4: Overview on geometries of X80 plates produced at SMGB

The first SMGB X80 plates were developed and produced according to specifications with a focus on the elevated strength level with no special requirements on base material- and HAZ-toughness. During the 25 years of development, more and more emphasis was laid on toughness behaviour [4]. Since 2002, SMGB has produced X80 plates thicker than 25 mm, which pose an additional challenge compared to the first X80 plates with smaller wall thicknesses. The toughness development for these plates since 2002 is illustrated by fig. 4 and 5. The Charpy toughness energy as well as the shear area fraction of Batelle drop weight tear tests were constantly increased. The Charpy energies in fig. 5 show that in years 2002 to 2006 the energy in the upper shelf reaches values of approximately 230 to 250 J, down to a test temperature of 10 °C. In 2007 the determined energy in the upper shelf was 270 J and in 2008 more than 300 J was determined. At the same time, the temperature of the upper shelf decreased to -40 °C in 2007 and finally to -50 °C in 2008.

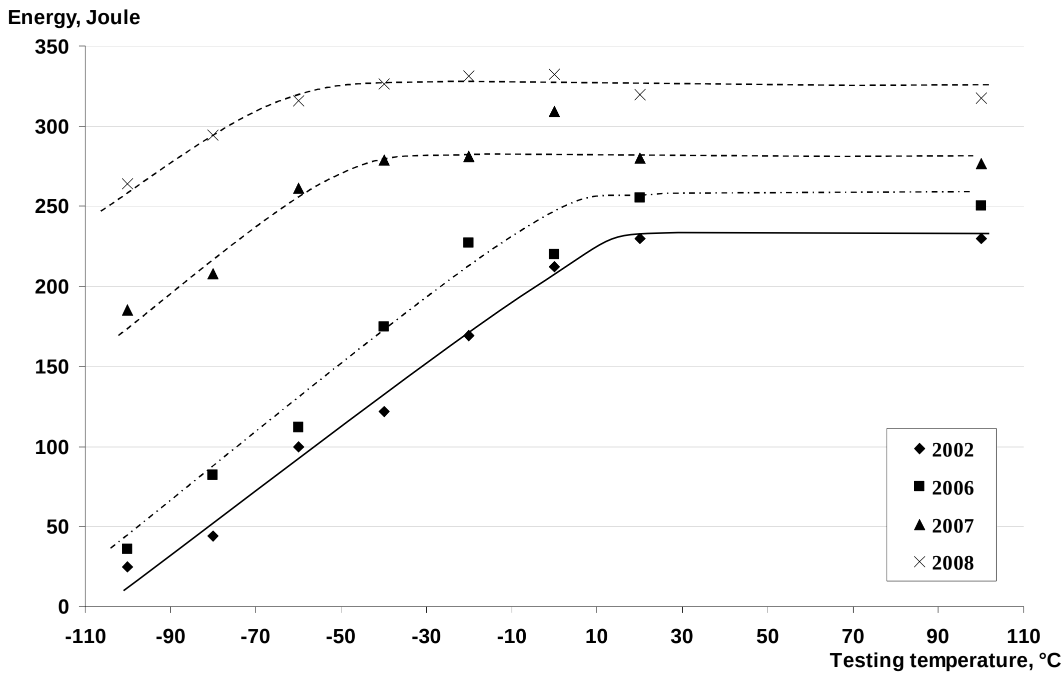

Fig. 5: Development of Charpy requirements for SMGB X80 plates since 2002 for plate thickness from 25 to 30 mm

A similar trend can be seen in the development of the shear area fraction of the BDWT-test results, which shows that the temperature for 85 % of shear area fraction decreases from 0 °C in 2002 to -20 °C in 2006 to the current temperature of -40 °C, which was reached in 2008 (figure 6).

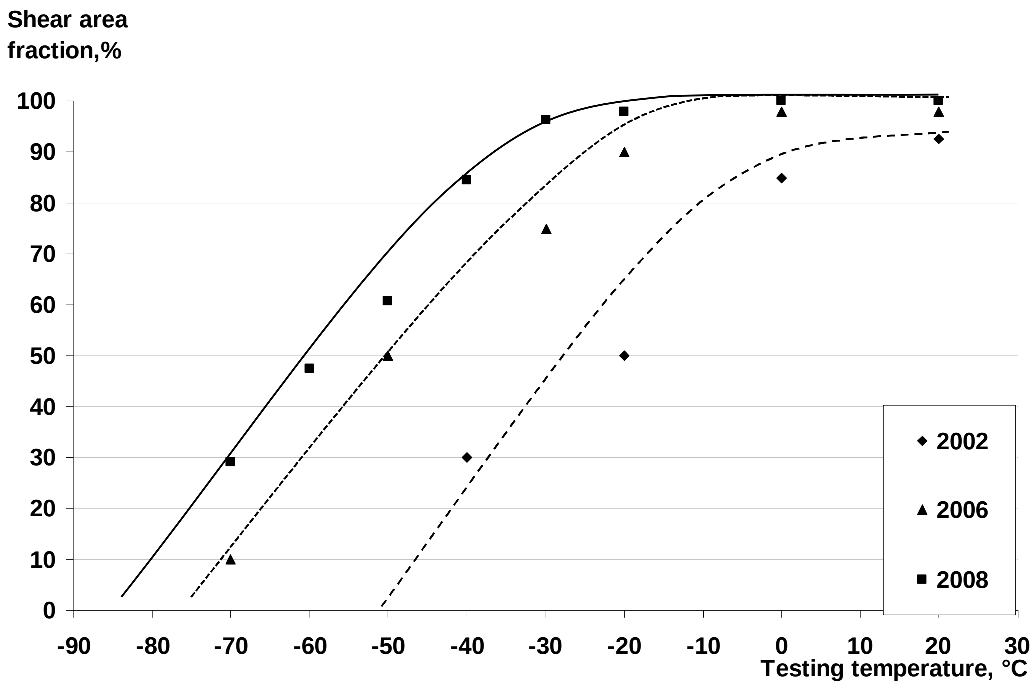

Fig. 6: Development of BDWTT requirements for SMGB X80 plates since 2002 for plate thickness from 25 to 30 mm

These challenging requirements were met by the material and process development while the alloying content was reduced at the same time (see fig. 7). This reduction improved the weldability of the plate material and allowed material costs to remain in a reasonable range.

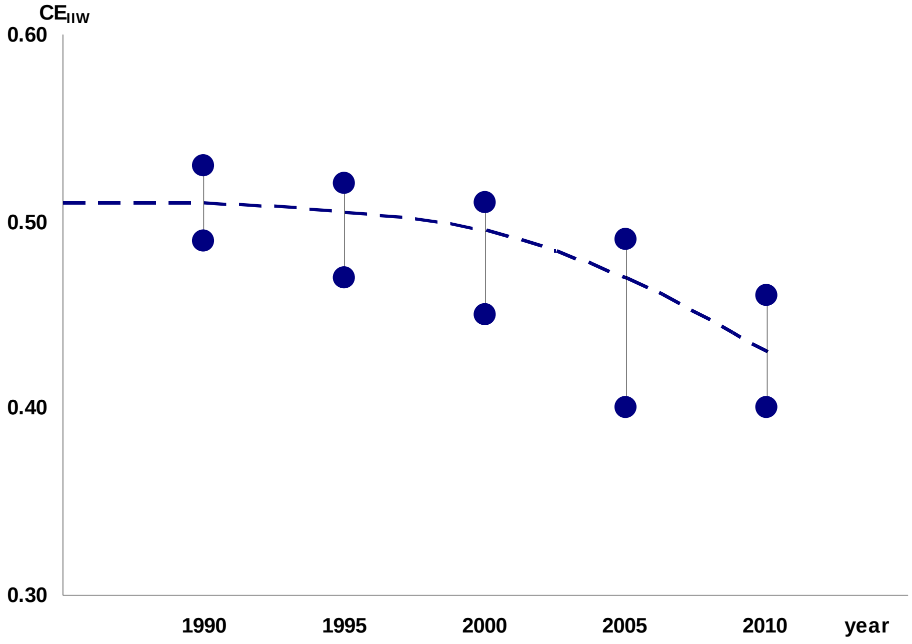

Fig. 7: Development of Carbon Equivalent CE$_{IIW}$ for SMGB X80 plates

Besides afore mentioned development aims, a more economical goal became increasingly important during the recent years of volatile alloying element prices. In order to keep material costs in an appropriate range, several attempts were made at SMGB to reach a certain degree of flexibility in terms of alloying concepts for X80 products. As an example, on a regular basis SMGB received orders for X80 plates with a thickness of around 20 mm. Since X80 pipes, respectively X80 plates compete with X70 pipes with an increased thickness, it is of essential importance to keep the alloying cost for these plates on a competitive level. Therefore the development goal was to have at least two different alloying concepts available for the same products and the same set of requirements. Laboratory and large scale rolling trials resulted in two types of steel which are shown in table 1 [**5**].

Table 1: Steel types for X80 plate with t= 20 mm

	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

Both steels were used for large scale production. As given in fig. 8, the results in terms of mechanical properties fulfilled all customer requirements. With these two alloying concepts SMGB was able to react on the alloying price development in order to keep the cost for X80 material for the customer on a competitive level.

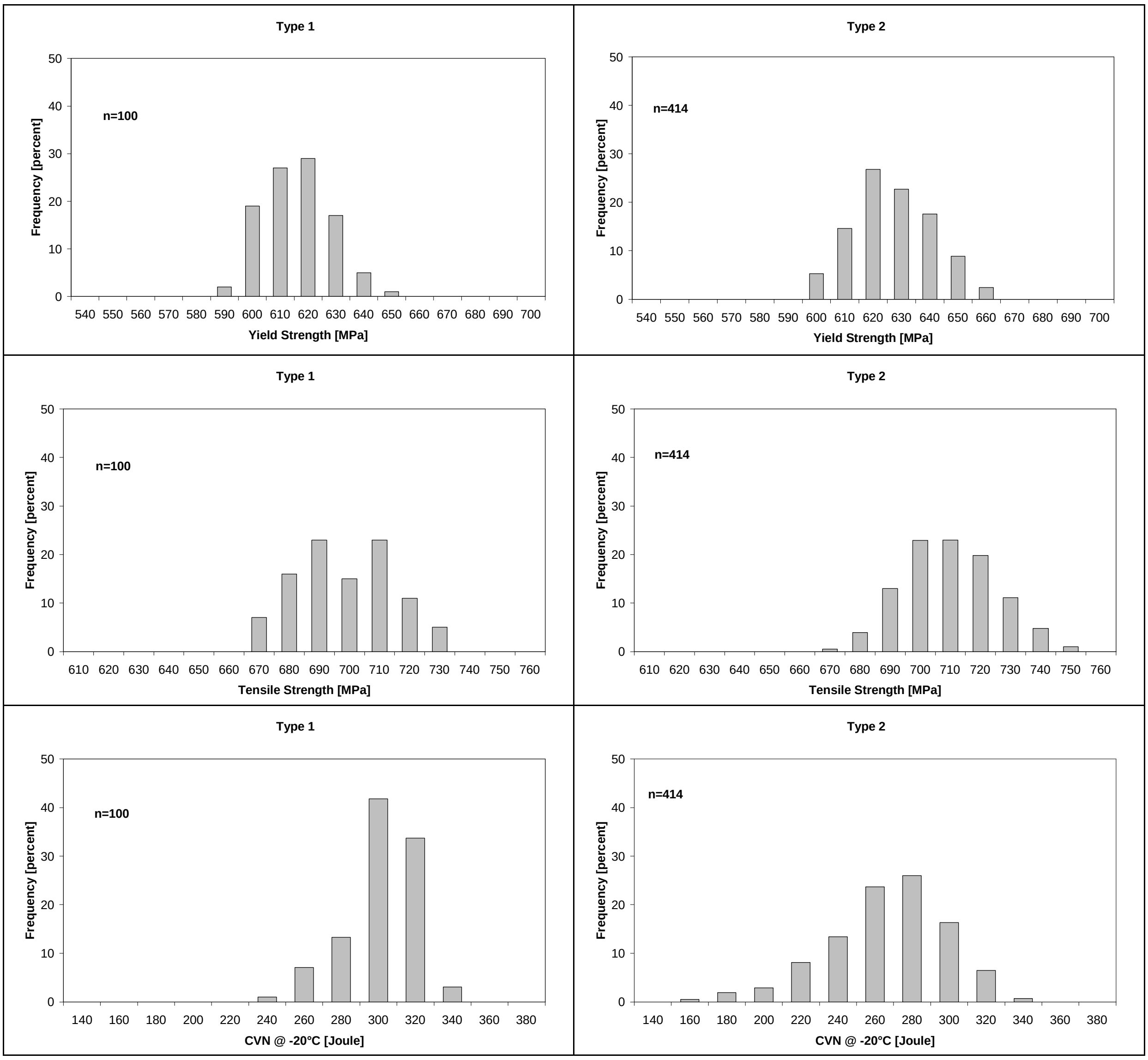

Fig. 8: Production results of X80 plates (t=20 mm) for two different types of steels

2. X80 PLATES FOR LINE PIPE APPLICATION IN ARCTIC REGIONS

Our low temperature products are designed for use in extremely cold environments, where beside the strength the avoidance of brittle fracture behaviour is of major concern. The newest plate product is developed to guarantee fully ductile failure behaviour at temperatures as low as -40 °C and also shows high crack arresting behaviour due to its fine arranged bainitic microstructure. Compared to ferritic-pearlitic microstructures, where the appropriate microstructures are developed by minimizing the austenite grain size, the bainitic microstructures are controlled by a combination of rolling and cooling parameters. In order to create the optimum microstructure for low temperature application, process parameters as the rolling parameters below the TNR, the cooling rate of the accelerate cooling and the final cooling temperature have to be adjusted. For our arctic grades the bainitic microstructure consists of a granular structured primary phase and very fine secondary phase particles, which are enriched with carbon. The granular primary phase nucleates at high temperatures and grows rapidly due to the high undercooling, which leads to a high number of low angle grain boundaries in the microstructure. Due to this grain structure and the dislocation density of the primary phase, the generated microstructure has a perfect combination of strength and toughness. The granular primary phase and very fine arranged hard second phase particles, which hinder the dislocation mobility, results in very high energy absorption and thereby insures an excellent crack arresting behaviour. An example for the microstructure is shown in figure 9.

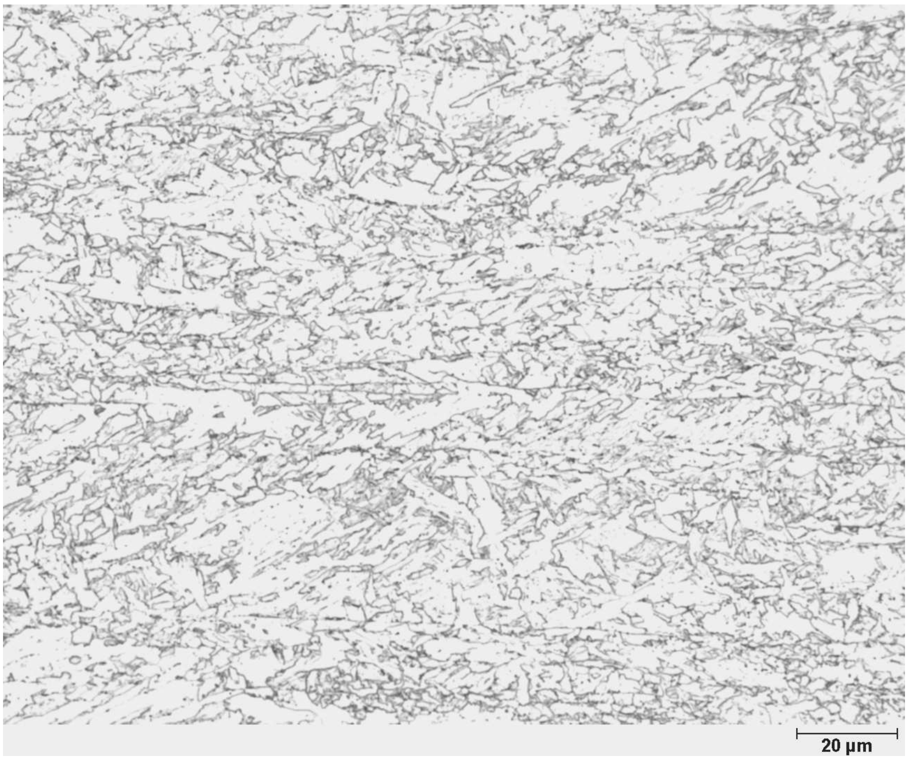

Fig. 9: Microstructure of the X80 grade

In the following the results of the last production campaign for plates with a thickness of 28 mm for arctic application are shown. The requirements for the final pipes, made from these plates are summarized in table 2:

Table 2: Pipe requirements (X80, wt = 28 mm)

$Rt_{0.5}$ transverse, MPa	$Rt_{0.5}$ longitudinal, MPa	Rm transverse, MPa	Rm longitudinal, MPa	A5, %	Y/T	CVN @-40, J/cm²	BDTW @-20, %	
							SV	AV
min. 555	min. 500	min. 640	min. 610	min. 18.0	max. 0.92	min. 250	min. 75	min. 85

The achieved average mechanical properties for a production campaign of more than 5000 plates are presented in figure 10. The values for the tensile strength were in average 675 MPa in transverse direction and 650 MPa in longitudinal direction and for the yield strength an average of 620 MPa and 530 MPa. The corresponding average yield-to-tensile ratio was determined to be 0.92, which was sufficient for a pipe production.

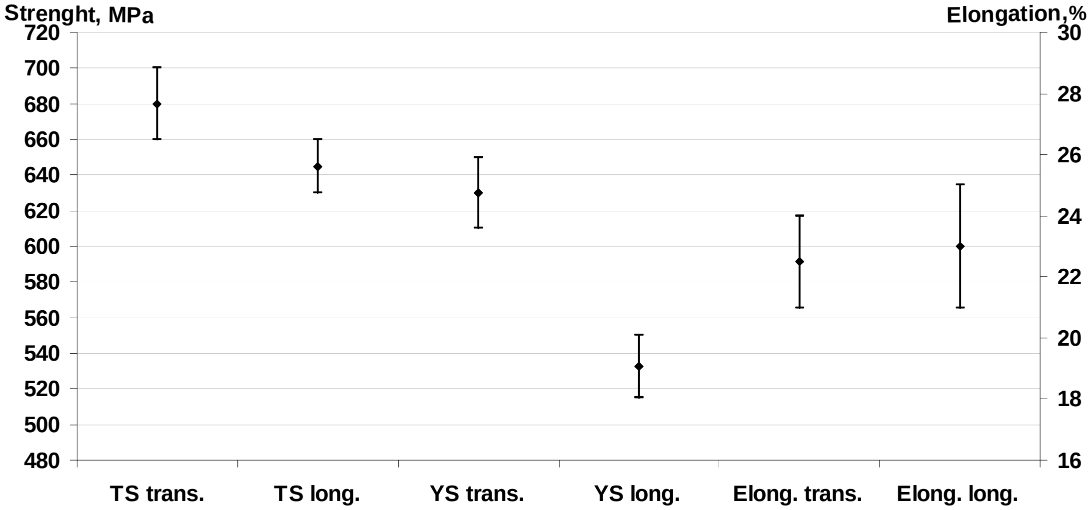

Fig. 10: Mechanical properties of the last production campaign of X80-plate with a thickness of 28 mm

As for all arctic grades the main focus during the production lies on the toughness properties. As a measurement for toughness the energy determined in Charpy V-notch tests can be seen in figure 11. In this figure the average energy of the production is shown. The energy in the upper shelf was determined to be in average approximately 350 J/cm².

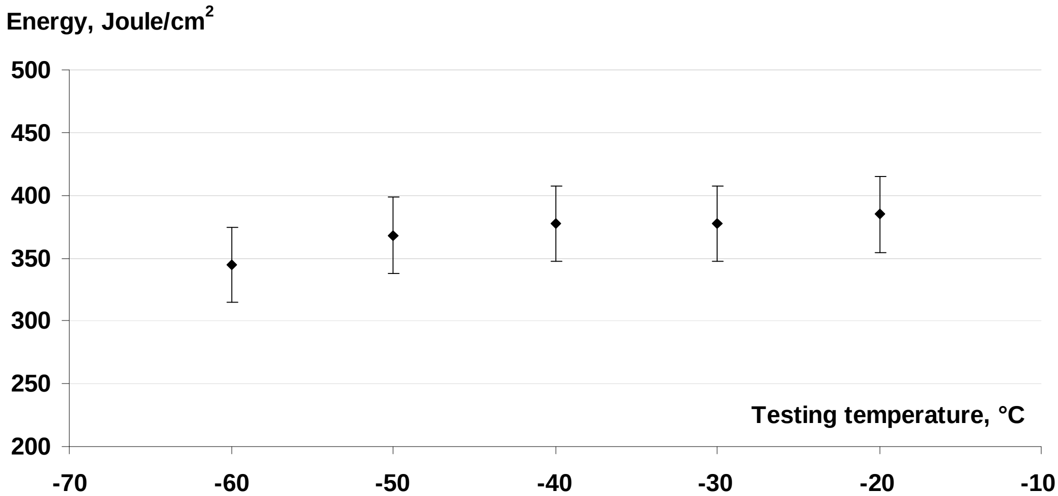

Fig. 11: Measured energy consumption in Charpy V-notch tests of the last production campaign of X80-plate with a thickness of 28 mm

As the production of X80 and plates with higher strength levels is done via accelerated cooling after the rolling, the cooling device has to be adjusted perfectly in order to guarantee homogeneous properties within the plate. The distribution of the mechanical properties over the length for an example plate from the production is shown in figure 12. This variation in local properties is similar to plates rolled without accelerated cooling and following figure 12, it can be stated that the mechanical properties are homogeneous over the complete plate.

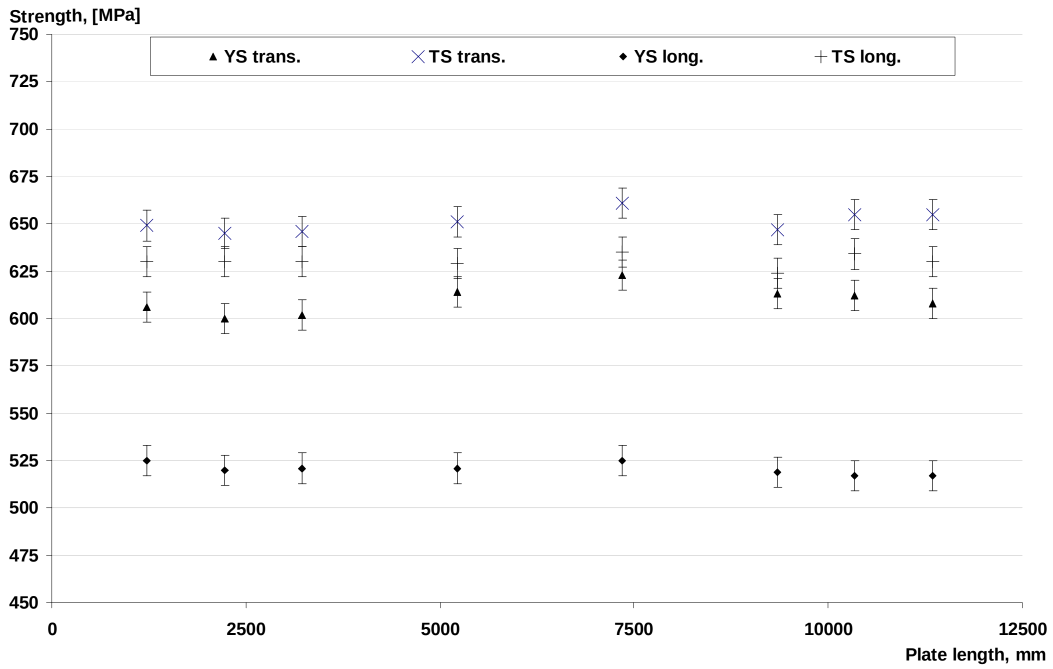

Fig. 12: Strength distribution over the plate length

Beside the mechanical properties the weldability which is represented by the carbon equivalent of the material is of great importance. In order to guarantee a good weldability, plates up to thickness of approximately 30 mm can be produced with a carbon equivalent of 0.45.

3. HIGH STRENGTH PIPE BENDS UP TO STEEL GRADE API X100

Fabrication of hot induction pipe bends in high strength material grade X80 in the bending plant of Salzgitter Mannesmann Grobblech started in the early 1990s. The first order consisted of 650 bends (1300 t) in the dimension 48" x 22 mm wt. for the Werne to Schlüchtern gas pipeline project of Ruhrgas in Germany **[6].** This project was followed by several pipeline projects in the UK. Up to 2007 in total 2740 bends have been produced by SMGB, as can be gathered from figure 13 **[5]**.

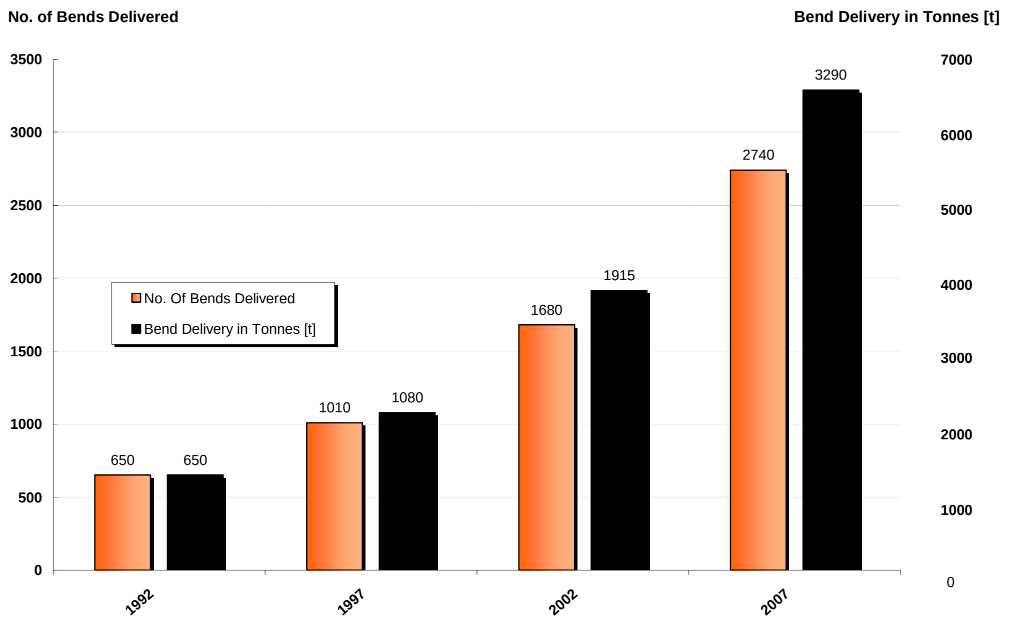

Fig. 13: Delivery of bends in material grade X80 from SMGB (cumulated)

The production of high strength large diameter hot induction bends from TMCP plate material poses severe technological challenges for the production process, maintaining excellent mechanical-technological properties and weldability. Consequently the availability of intensive know-how on manufacturers' side is essential. Development and evaluation work of SMGB on high strength material for bends is including research of appropriate base material compositions, weld seam requirements, bending parameters in terms of balanced temperature control during induction heating, full scale burst testing, detailed microstructure investigations, mechanical testing and field weldability assessment **[7].**

The well balanced design of the chemical composition for the TMCP mother plates is essential to avoid downgrading of the material due to the process related heating during bending **[8].** SMGB can cover the full chain of pre-material supply within company group own mills and is consequently able to respect the necessary requirements for induction bend fabrication right from the start.

Material development was recently focused on bends in material grade X100. Together with Salzgitter Mannesmann Research Centre (SZMF) several alloying concepts were investigated on laboratory heats small size slabs were TMCP rolled in the lab, followed by a heat treatment, typical for the bending process. After mechanical-technological investigation the optimised design for the chemical composition was settled for a full scale qualification in the range of 0.51 $CE_{(IIW).}$ (see figure 14).

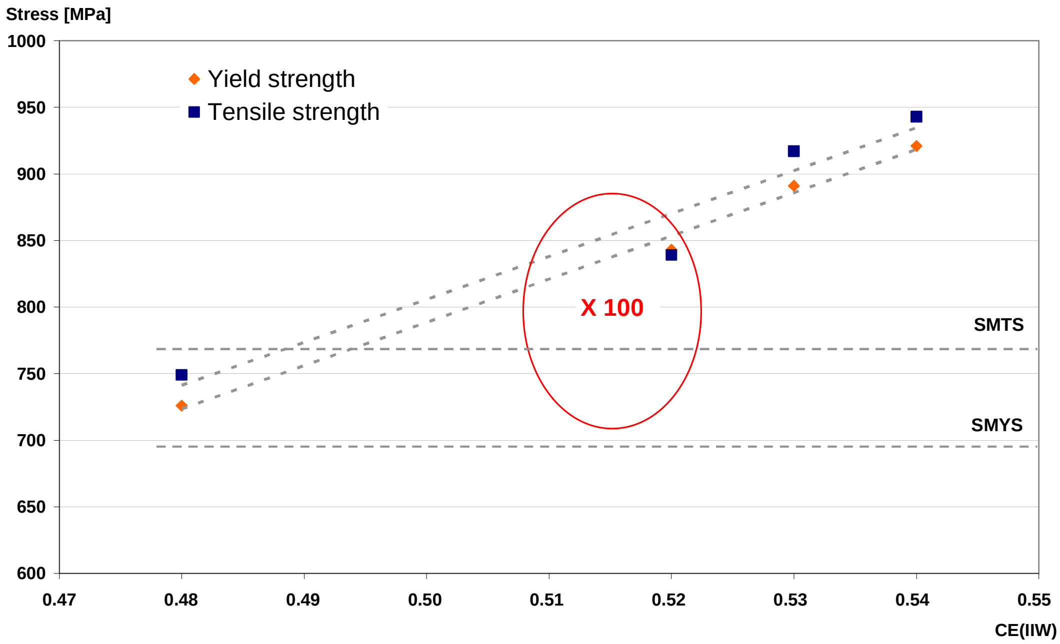

Fig. 14: Relation between carbon equivalent and tensile properties on TMCP test plates after simulated heat treatment of induction bending process

Four test bends in the dimension 48"x 22 mm wt. with a bending radius of 5D (6100 mm) were produced. On one 45° bend a full scale hydrostatic burst test was performed at SZMF (see figure 15). The ultimate burst pressure was 330 bar, which is well beyond common operating pressures. The calculated burst pressure level according to Barlow equation **[9]** for 758 MPa SMTS results in 278 bar and thus 50 bar below the actual measured value. The initial water capacity of the pipe bend was 8500 litres. During pressurisation the bend was subjected to a volumetric increase of about 4 %.

Fig. 15: Set up of full scale burst test on a high strength 48” bend at SZMF

Actually, high grade material is not capable of delivering significant amounts of plastic strain. Circumferential strain is limited to 1.0 %, when measured on X100 line pipe. The integral circumferential failure strain in the present bend was 1.3% on average. Single values up to 2 % of circumferential plastic strain were measured in the bent arc, indicating a sufficient safety against localised failure behaviour.
This full scale qualification demonstrates that SMGB is well prepared for the first delivery of induction bends in material grade X100.

SUMMARY

The development of high strength steel plate at SMGB was recently focussed on the improvement of toughness properties, weldability and material cost. Heavy plate for linepipe in steel grade X80 was produced up to a thickness of 40 mm and up to a width of 4,500 mm. Upper shelf behaviour for Charpy testing down to a test temperature of -50 °C was achieved. 85 % shear area fraction in the DWT test is certainly reached at -40 °C.

These improvements were reached, while the carbon equivalent as a measure for weldability could be limited to 0.45. This ensures excellent weldability for the pipe manufacturer as well as for the field welding of the later pipe. SMGB developed alternative alloying concepts and steel types in order to react on changing alloying element prices. The SMGB pipe bending plant produced the first X100 pipe bends and characterised them in a burst test.

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