High Strength Large Diameter UOE Line Pipes Optimised for Application in Remote Areas and Low-Temperature Service

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Abstract

The last decades have seen a steady increase in the demand for high strength linepipe steels. These offer the most economical option to transport large gas volumes at high pressures from remote areas to the market. Since the beginning of the 1980s, high strength heavy plates, large diameter pipes and pipe bends were developed and produced at Salzgitter Mannesmann Grobblech (SMGB) and EUROPIPE in cooperation with Salzgitter Mannesmann Forschung (SZMF). While the focus was initially on tensile properties in hoop direction only, low-temperature toughness and weldability have gained growing significance recently, as gas resources are developed in increasingly hostile environments. This has spurred research activities to optimize the alloy and process design along the complete process chain, which have led to major improvements.

Modern X80 high-strength heavy plates used in the production of UOE pipes are generally produced by thermomechanical rolling followed by accelerated cooling (TMCP). This processing route results in a microstructure that consists predominantly of bainite. The combination of high strength and high toughness of these steels are a result of the microstructure realised by TMCP and are strongly influenced by the rolling and cooling conditions. The improvement of the properties of the weld is a result of an optimization of the base metal composition and the welding process. Because of the continuous development efforts devoted to the optimization of high strength large diameter pipes, they have become daily business for both SMGB and EUROPIPE. Within this paper, an overview of the improvements of low-temperature toughness of heavy plates and large diameter UOE pipes is presented.

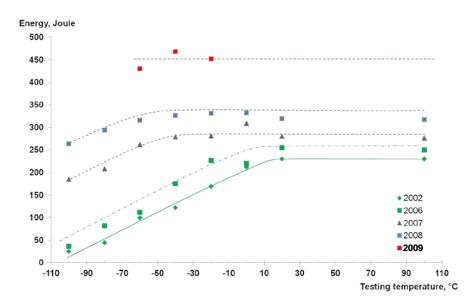
1. Introduction

High strength line pipe steels offer an economic advantage compared to lower strength grades as they allow a reduction in wall thickness of the pipe at the same operating pressure. This leads to savings with regard to raw materials, transportation and field welding. Conversely, they allow an increase of the operating pressure at the same wall thickness. Since the first application of X80 large-diameter pipes more than 25 years ago, the combination of mechanical properties required by customers has become increasingly complex, due to the strong worldwide interest to develop remote natural gas resources in hostile environments. These can include pipeline

operation under arctic conditions or in areas with ground movement. High deformability and low-temperature toughness are therefore critical requirements in order to ensure pipeline safety. The optimisation of the toughness has therefore been a strong focus of development in order to ensure crack arrest at low temperatures. However, it has been shown that while existing criteria predict crack arrest reasonably well when compared with the results of full scale tests up to the X70 strength level, these do not appear safe in the case of high strength grades [1]. A high total energy in the drop-weight-tear (DWT) has been recommended as a design guideline for crack arrest [2].

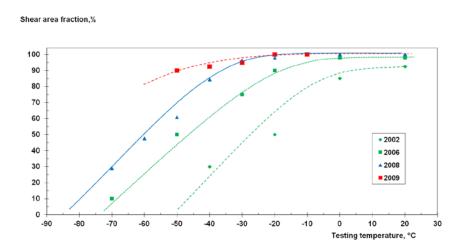
Since the beginning of the 1980s, heavy plates, pipes and pipe bends of X80 were developed and produced by SMGB and EUROPIPE and have become daily business for both companies as long as the requirements are merely according to EN 10208-2 [3], API 5L [4] or equivalent. In recent years, however, the complexity of requirements for line pipe materials has increased steadily with regard to toughness and weldability. SMGB and EUROPIPE have reacted to these demands with continuous alloy and process development in cooperation with SZMF in order to offer economically feasible solutions and guarantee safe operation for these scenarios.

Figure 1: Development of Charpy properties and requirements for SMGB X80 plates since 2002 for a plate thickness between 25 and 30 mm



The first X80 pipes were developed and produced according to specifications with a focus on elevated strength level with no specific requirements on low-temperature toughness in the base metal or the heat-affected zone (HAZ). Since then, more and more emphasis was laid on toughness [1-4]. Since 2002, SMGB has produced X80 plates above 25 mm wall thickness, which poses an additional challenge compared to the first X80 plates with lower wall thickness. The toughness development for X80 heavy plates since 2002 is illustrated in Figure 1 and 2. The requirements regarding minimum Charpy impact energy as well as the shear area fraction in drop-weight-tear (DWT) tests increased constantly. As shown in Figure 1, the upper shelf energy was raised from a level of 230-250 J at a testing temperature of 10°C in 2002 to 2006 to 450 J at -60°C in 2009. This went hand in hand with an improvement of the shear area in the DWT-test, where the 85% shear area transition temperature was lowered from 0°C down to -50°C in 2009.

Figure 2: Development of shear area in the DWT-test for SMGB X80 plates since 2002 for a plate thickness between 25 and 30 mm



Submerged-arc welding of large diameter pipes requires a high heat input in order to achieve the welding speeds necessary for practical production. This leads to significant changes in the microstructure in the heat-affected zone (HAZ) [10]. These include grain coarsening and the formation of carbon-rich constituents in a bainitic matrix in the vicinity of the fusion line.

It has been demonstrated that the alloy design of the plate material in combination with the processing parameters during welding plays a key role for achieving a high level of HAZ-toughness at low temperatures [11]. Modern linepipe steels for large-diameter pipes are low-carbon steels with a carbon content in the range of 0.03-0.10 wt.% and are microalloyed with niobium. The basic alloy design for X80 linepipe steel is shown in Table 1. Continuous alloy and process development made it possible to achieve the X80 strength level and reduce the level of alloying elements at the same time. This is illustrated in Figure 3 which shows the development of the carbon equivalent (CE_{IIW}) of X80 since 1990. The reduction of the CE_{IIW} improved the weldability of the plate material while material costs maintained in a reasonable range. Achieving the balance of all material properties places tight restrictions on the alloy design and processing strategy at all stages of production. Key aspects of production of X80 large-diameter linepipes are illustrated and results of production are presented in the following sections.

Figure 3: Development of the carbon equivalent CE_{IIW} of X80 since 1990

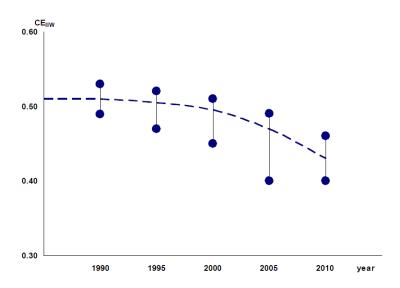


Table 1: Alloy design for X80 large diameter pipe applications (wt.%)

С	Mn	Nb+V+Ti	Others		
< 0.07	>1.6	<0.15	Cu, Cr, Ni, Mo		

2. The effect of thermomechanical rolling on low-temperature toughness

Thermomechanical rolling in combination with accelerated cooling (TMCP) is the key factor to achieve the X80 strength level. This process makes it possible to obtain a highly homogeneous microstructure over the wall thickness with a grain size of only 2-5 μ m. In cases where the focus lies on low-temperature toughness, the processing strategy for the production for X80 consists of thermomechanical rolling followed by accelerated cooling from above the Ar₃-temperature. This rolling strategy typically leads to a microstructure that contains a bainite volume fraction of 80% or higher and minor volume fractions of ferrite and martensite, as shown exemplarily in Figure 4 in the light-optical micrograph of heavy plate material.

During rolling, the deformation is divided in two separate temperature regimes. In the first stage, deformation takes place at temperatures where recrystallisation of the austenite is possible between rolling passes. This leads to the formation of equiaxed austenite grains with a reduced grain size compared to the as-cast condition. In the second stage, recrystallization between passes is inhibited by niobium carbide precipitates and a pancake austenite structure is formed. In this stage, a high density of nucleation sites for the ensuing phase transformation is generated which leads to the low grain size of these steels. It has been shown that the processing parameters in this stage have a significant effect on the low-temperature toughness, especially on the shear area in the DWT-test and this was linked to the microstructure [8,9].

Light-optical microscopy offers only limited possibilities to characterize the microstructure quantitatively and to investigate a correlation with processing parameters because of the small size of the features. For this reason, high-resolution scanning electron microscopy (SEM) with its inherent higher resolution in combination with electron backscatter diffraction (EBSD) is far better suited to

describe the microstructure in detail and has therefore gained growing significance for materials development. An example of X80 heavy plate material observed by SEM is shown in Figure 5. In this case, a homogeneous distribution of carbon-rich constituents with a size of below 2 µm was observed.

Figure 4: Typical microstructure of an X80 heavy plate at a magnification of 500:1 obtained by light-optical microscopy

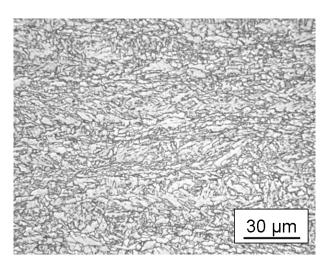
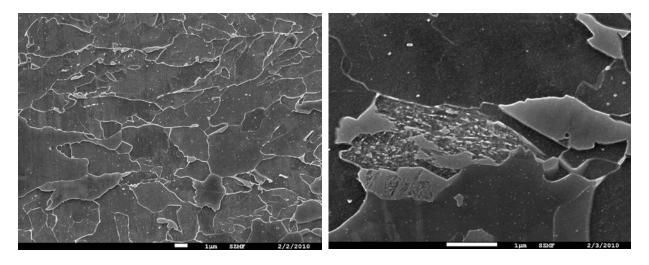


Figure 5: Microstructure of an X80 lab-rolled plate (left) and carbon-rich constituents (right) obtained by scanning electron microscopy



EBSD measurements of the crystallographic texture have demonstrated that the low-temperature toughness is linked to the microstructure and the processing parameters during TM-rolling and accelerated cooling [9]. In a laboratory investigation carried out at the SZMF in cooperation with SMGB with the aim to find optimum processing conditions for the production of X80 plate material with excellent low-temperature properties in the DWT-test, it was found that the intensity of a texture component that is known to have a detrimental effect on toughness [12], the rotated cube component {100}<110>, is higher if an excessive final rolling temperature (FRT) is used in the second stage of rolling. This can be counteracted if a lower final rolling temperature closer to the Ar3-temperature is selected [9]. The intensity of the {113}<110> and {112}<110> components is then higher than that of the production of heavy plates

with 23.8 mm and 27.7 mm wall thickness were modified and the texture of samples taken from production was investigated.

The results of the texture measurements are shown in the two-dimensional sections of the orientation distribution functions (ODF) at $\phi_2\text{=}45^\circ$ in Figure 6. The samples taken from X80 production at SMGB showed a slightly higher volume fraction around the rotated cube orientation compared to material from the laboratory trials rolled at a low final rolling temperature. This was, however, counterbalanced by high volume fractions around the {113}<110> (25°) and {112}<110> (35°) components. This is also reflected in the skeleton plots for the alpha fibre $(\phi_1\text{=}0^\circ,\ \phi_2\text{=}45^\circ)$ in Figure 7 which shows that the intensity of the rotated cube component at $\Phi\text{=}0^\circ$ relative to the other texture components is highest for the laboratory-rolled plate rolled at a high final rolling temperature. All the other investigated materials show a peak that is shifted away from the position $\Phi\text{=}0^\circ$ towards the {113}<110> and {112}<110> components along the alpha fibre which has proven to be beneficial for the low-temperature toughness.

Figure 6: ODFs at ϕ_2 =45° of laboratory-rolled plates and mill material at midthickness

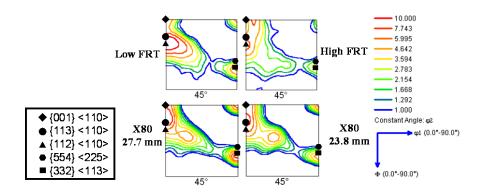
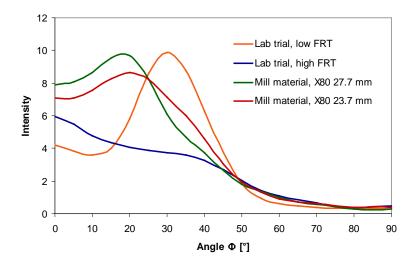


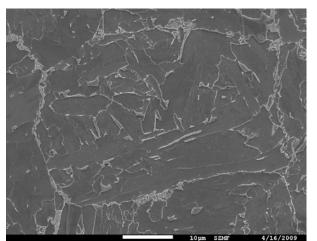
Figure 7: Skeleton plot along the alpha-fibre of laboratory-rolled plates and X80 mill material at mid-thickness

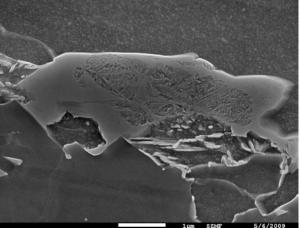


3. The effect of alloy design on HAZ toughness

The changes in the microstructure close to the fusion line that take place in production of large-diameter pipes during double submerged arc welding can have a pronounced negative effect on the toughness of the HAZ. Significant austenite grain coarsening takes place because of the high temperatures of above 1300°C reached in this region. Grain coarsening can be inhibited only to some degree by the addition of titanium which forms stable nitrides that exert a pinning force on the grain boundaries. However, exact control of the titanium and nitrogen levels is required in order to prevent the formation of coarse TiN precipitates that have a negative effect on the toughness in the HAZ [13]. Niobium and vanadium also form carbonitrides, but can prevent grain coarsening only at lower temperatures, because of their higher solubility in the austenite [10, 14]. The large austenite grain size retards the austenite-ferrite transformation and usually leads to a coarse bainitic microstructure with a low volume fraction of carbon-rich constituents close to the fusion line. An example of the microstructure in the HAZ is shown in Figure 8.

Figure 8: SEM-image of carbon-rich phases at the prior austenite grain boundary and within grains in the HAZ (left) and carbon-rich constituent (right)

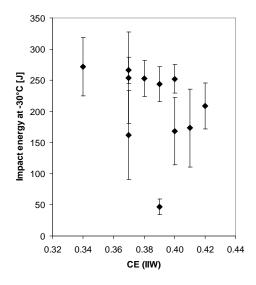


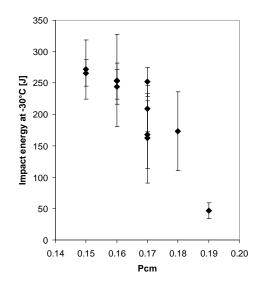


Classically, the carbon equivalent is used as an empirical measure for the weldability of steels and is known to correlate with the maximum hardness. However, it was not designed to predict the effect of individual alloying elements on HAZ-toughness. In submerged-arc welding trials on laboratory heats and mill material carried out at the SZMF in cooperation with EUROPIPE, the effect of alloying additions on the HAZ toughness at -30°C in the FL 50/50 position and on the microstructure was analysed [11]. The strength level in these trials was varied in the range from X65 to X80. The wall thickness was held constant at 30 mm and the welding parameters were identical in each case in order to allow a better comparison.

As illustrated in Figure 9, the results show that the HAZ toughness does not correlate well with the CE_{IIW}. However, the correlation improved markedly if the toughness was compared against the Pcm. Quantitative analysis of the carbon-rich constituents in the microstructure showed that the volume fraction correlates well with the HAZ toughness. In this investigation, a high level of HAZ toughness was maintained in those cases where this volume fraction was below 6%.

Figure 9: Mean impact energy and standard deviation at -30°C in the FL 50/50 position vs. the CE_{IIW} (left) and Pcm (right)





It was found that selecting low levels of carbon of 0.06% and silicon of <0.1% is an effective measure to reach a high toughness in the HAZ. The results also showed that an increase of the manganese content from 1.6% to 1.8% did not have a detrimental effect. In order to reach the X80 strength level, however, further alloying additions are necessary and their levels depend on the wall thickness of the pipe. A combination of copper, nickel and molybdenum that was investigated in the welding trials constitutes a possible strategy for the grade X80. However, this led to a lower level of HAZ toughness with a mean impact energy of about 170 J and considerable scatter compared to those cases, where no molybdenum was added. This shows that finding the correct balance of the alloying additions is a prerequisite for a high toughness in the HAZ. The fact that higher alloying additions are generally necessary in order to reach the X80 strength level compared to lower strength grades and that this has an effect on the HAZ toughness has to be taken into account in pipeline design.

4. Results of K65 pipe production

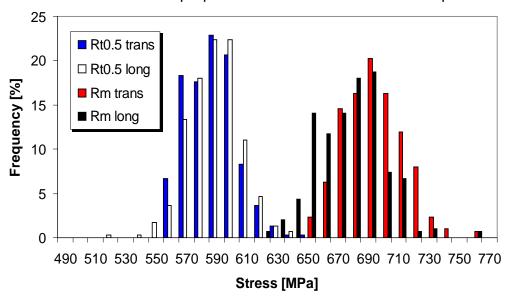
EUROPIPE produced pipes of the grade K65 with an outer diameter of 56" and a wall thickness of 27.7 mm for the Russian Bovanenkovo-Ukhta project [15]. The composition that was used is shown in Table 2.

Table 2: K65 steel composition (wt.%)

С	Mn	Р	S	Nb+V+Ti	Cu+Cr+Ni+Mo	CEIIW	Pcm
<0.08	>1.6	<0.02	<0.003	<0.15	>0.6	< 0.45	<0.23

The grade K65 corresponds to an X80 with an increased minimum ultimate tensile strength requirement of 640 MPa compared to 621 MPa for an X80. For this project, tensile testing was also required in longitudinal direction. The yield strength requirement in longitudinal direction was, however, lowered to 500 MPa while 555 MPa were specified in transverse direction. The results of the tensile tests in both orientations of more than 300 heats tested during the initial stage of production are summarized in Figure 10.

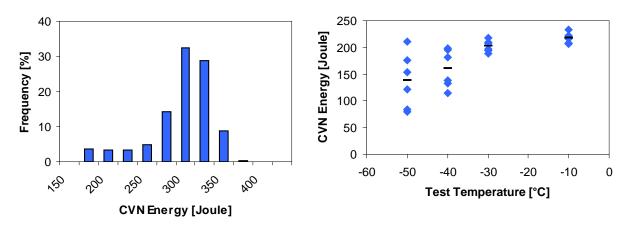
Figure 10: Distribution of tensile properties of OD 56" x 27.7 mm K65 production



The average yield strength was 584 MPa and 586 MPa in transverse and longitudinal direction. A small number of yield strength values for the longitudinal direction were in the range of 520-550 MPa, whereas the majority fulfilled the more stringent requirement for the transverse direction. An average ultimate tensile strength in transverse direction of 687 MPa was observed and the anisotropy of transverse and longitudinal tensile strength values was only 15 MPa. It was found that the minimum values were lower in longitudinal than in transverse direction.

Special emphasis was put on the low-temperature toughness. The minimum required Charpy impact energy for the base metal at -40°C was 150 J. Only few values were below 200 J, as shown in the distribution of the Charpy energy in Figure 11. This illustrates that the base material showed upper-shelf behaviour consistently.

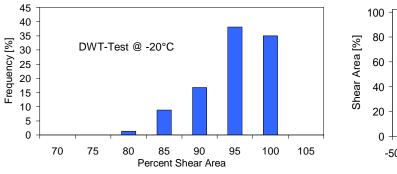
Figure 11: Distribution of the base metal CVN impact energy at -40°C (left) and the Charpy transition curve for the weld metal (right)

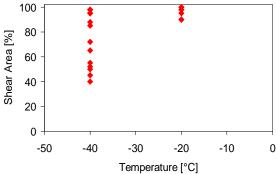


The level of the impact energy in the weld metal in the upper shelf was lower than in the case of the base metal with a value of about 200 J in the upper shelf, as shown in Figure 11, and did not vary for the outer seam, the inner seam or the root position. The toughness in the HAZ was, however, on a lower level. In addition, a mean shear

area of 85% in the DWT-test at a testing temperature of -20°C was required with minimum values of 75%. This posed the toughest challenge in production. As shown in Figure 12, this requirement was successfully fulfilled. In addition, tests were carried out at -40°C and demonstrated that the 50% shear area transition temperature lies below -30°C.

Figure 12: Distribution of the shear area in DWT tests of OD 56" x 27.7 mm K65 production (left) and comparison of shear area at -20°C and -40°C (right)





5. Conclusions

SMGB and EUROPIPE have been constantly involved in the improvement of highstrength grades since the early 1980s. While the initial focus was mainly on the yield strength and tensile strength, the requirements have become increasingly challenging with regard to low-temperature toughness, field weldability and material costs.

Because of the high interest to develop gas fields in hostile environments with operation under arctic conditions, a high level of low-temperature toughness and crack arrest capabilities have to be realised. This was achieved successfully by constant alloy and process development. Experiences and evaluations showed that it is essential to maintain tight control of the rolling parameters in order to guarantee excellent low-temperature toughness. It was found that the texture that develops during plate production has a strong impact on the low-temperature toughness and a lower final rolling temperature has a beneficial effect.

It was also demonstrated that the toughness of linepipe steels in the HAZ depends strongly on the base metal composition. A higher content of alloying elements is generally necessary in order to reach the X80 strength level. For this reason, the alloy design can run counter to a high level of toughness in the HAZ. It is therefore important to find the optimum balance between the strength of the base metal, on the one hand, and the HAZ-toughness, on the other hand.

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