Development of grade X120 pipe material for high pressure gas transportation lines

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ABSTRACT

The increasing demand for natural gas will further influence the type of its transportation in the future, both from the strategic and economic point of view. Long-distance pipelines are a safe and economic means to transport the gas from production sites to end users.

High-strength steels in grade X80 are nowadays state of the art. Grade X100 was recently developed but not yet utilised. The present-day technical limitations on the production of X120 line pipe namely the steel composition, the pipe forming and the welding are addressed in this paper. Production test results on X120 pipes are presented to describe the materials properties.

A low carbon and low P_{CM} steel with VNbTiB microalloying concept is used. In the plate rolling the main attention is turned to the heavy accelerated cooling. The large spring back that occurs during the U-forming step of the UOE process is one of the most complex aspects in forming X120. To handle this aspect FEM calculations were used to modify the forming parameters and to optimise the shape of the U-press tool. For optimising the existing welding procedure with respect to an avoidance of HAZ softening, a low heat input welding technology and new welding consumables were developed.

1. Introduction

The development of high-strength steels is intensified world-wide to use the economic advantages. As the development of grade X80 is finished this grade is state of the art for high pressure gas pipelines. Grade X100 has reached the stage of full-scale testing. Some pipe manufactures have produced large-diameter pipes in grade X100 on a larger scale for extensive research on this grade. First demonstration lines are in use or will be installed in the near future.

Further project cost reduction by using even higher steel grades such as X120 are possible /1, 2/. The reduction of project cost are presented as a result of the sum of the following different benefits:

- reduced quantity of steel required and therefore reduced material cost
- lower pipe transportation cost
- lower pipelaying and construction cost
- Reduced compression cost.

The use of grade X 80 linepipe in the construction of the first Ruhrgas X80 pipeline led to a material saving of about 20 000 t, compared with grade X 70 pipes (**Figure 1**), through a reduction of the wall thickness from 20.8 mm for X 70 to 18.3 mm for X 80. This resulted also in a reduction of the pipelaying costs because of reduced pipe transportation costs and greatly reduced welding costs through reduced welding times needed with thinner walls. The use of materials with still higher strength such as grade X 120 is challenging as further cost savings for the gas transport companies are possible.

Consequently EUROPIPE started in close co-operation with Dillinger Hütte and Salzgitter Mannesmann Forschung the development of a line pipe steel whose mechanical-technological properties meet the requirements on grade X120. The target properties for this new steel grade had to be extrapolated from known high-strength grades like X80 because even higher grades like X90, X100 and X120 are not yet specified in the current line pipe standards such as API5L.

To shorten the period of development and to gain the maximum benefit from the close co-operation the process of development was started with the most challenging aspects at the same time. The first promising results were available shortly after commencing the work /3/. Because of the experience gained from X100 it was certain from the beginning that the well established welding process for the longitudinal weld seam and the UOE-process had to be modified for this new high-strength steel grade. Even the development of completely new processes could not be ruled out.

This paper gives an overview of the development of grade X120 pipe material. The experiences made during this development will also be addressed in this paper. Special attention is focused on the effect of boron on the mechanical properties of the base material and on the development of pipe forming and modified welding technologies which had to be adapted from the existing and well established processes. The production of pipes in grade X120 has just started with the first trial production so that a definite statement on the above mentioned possible cost savings has to be made when this investigation is finished.

2. Development of X120 pipe material

Target of development

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 summarised in **Table 1** /4, 5/.

Design of microstructure and chemical composition

The required properties of a steel in grade X120 are only reachable with a mainly baintic microstructure that predominantly consists of lower bainite. Due to the combination of a high dislocation density and a very fine scale substructure, so called domains, this lower bainitic microstructure is reasonable option for an ultra-high-strength level along with sufficient toughness properties.

To produce such a microstructure especially with a low C and low PCM steel the chemical composition had to be designed very carefully. The basic alloying system contains CuNiCrMo and the microalloying elements VNbTi. Besides these the microalloying element boron should also be effective. To improve the hardenability of the austenite the analysis contained sufficient effective boron. Boron has a strong retarding effect on the transformation of austenite to ferrite and with this supports the formation of the required bainitc microstructure. To intensify this effect the attention during the production of the mill heats had to be turned to a low carbon content in general. In particular the carbon content was within a certain scatter band. In the end this led to variation in the strength levels of the plates. Furthermore, the combination of boron with nitrogen and oxygen had to be avoided. With a manganese content of about 1.90 % the carbon equivalent CE_{IIW} of the chemical composition used in initial investigations was in a range of 0.50 % up to 0.55 %. The PCM value was approximately 0.23 %. The basic chemical compositions of the steel is summarised in **Table 2**.

Plate rolling process parameters

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 an best possible initial austenite grain size which is the starting point for the further control of the mechanical properties during the rolling process. Furthermore, an as high as 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 the 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 K/s and a cooling stop temperature below 400 °C are the main process parameters.

Plate production and properties

Based on these considerations for a fundamental concept of alloy design and choice of process parameters a series of heavy plates was rolled in a trial production. The mechanical-technological properties met the targets concerning yield strength, tensile strength, Charpy impact toughness, BDWT properties and microstructure, as can be seen in **Table 3**. A more detailed description of the plate is given in /6/.

By using narrow temperature ranges for the individual rolling stages, which were based on precisely measured A_{r3} temperatures, a very high strength level could be achieved. The values of the yield strength reached values of $\geq$ 840 MPa and the values of the tensile strength were $\geq$ 1000 MPa. Furthermore, impact energy values $\geq$ 231 J were measured at –30°C.

Modification of pipe forming parameters

One of the great challenges in the pipe forming of ultra-high strength plate with a relatively small wall thickness is the large spring back due to the greater elastic range of a material with high yield stress. Especially the U-forming step is affected by this spring back. It could lead to shells that cannot be inserted into the O-press.

Finite element calculations were carried out to support the optimisation of the U-ing process and the shape of the U-ing punch. The results of the FEM calculations are provided by **Figure 2**. The large spring back after an U-ing with a conventional U-press tool is visible here. Such a plate could not be inserted into the O-press. In addition to this the shape of the U-press was modified in the calculations, as can be seen from **Figure 3**, to find the best possible parameters for an adapted UOE-process. The newly calculated shape of the U-Press will lead to a reduction of the spring back. The plate could be inserted into the O-Press. Furthermore, it was assured that the ovality and peaking after O-ing were as well set to optimal value to avoid problems with the welding and expansion steps of the pipe production.

Aspects to be solved with respect to welding of the longitudinal seam

The multi-wire submerged-arc welding process used universally to deposit the two-pass longitudinal seam weld in pipe is associated with a high heat input and leads to aspects that cannot be underestimated in the case of the grade X 120 as described below.

The first aspect is the softening of the base material adjacent to the longitudinal seam weld. This problem is existent to some extent also in the case of materials in grades X 80 and X 100. To handle this aspect the X120 material contained a certain amount of vanadium to use its precipitation hardening effect.

The second aspect is associated with the continuing use of the proven submerged-arc welding and achieving adequate strength and toughness for the weld metal of the two-pass longitudinal seam weld in the highest strength material X 120. This problem had to be resolved by selecting a matching chemical composition for the weld metal alone and additionally by reducing the heat input per pass.

The average heat input per pass, which is at 2 kJ per cm of the weld and per mm of the pipe wall thickness, needed to be reduced considerably (e.g. to a value = 1.5 kJ per cm of the weld and per mm of the pipe wall thickness). Production experience available today in this connection is not sufficient to permit an assessment of the softening that occurs in the base material adjacent to the weld. This depends also on the pipe wall thickness. Finally, such an approach is limited by the need for a sufficiently overlapped welding and therefore adequate production safety.

Development of new welding consumables and low heat input welding technology

Extensive experimental work was done to develop a new wire and an optimal wire - flux combination for the longitudinal weld seam. For this, numerous seam welds were made in the laboratory with a wide range of welding conditions using X120 heavy plate material. **Table 4** shows the main chemical compositions of the different variants of the seam weld chemistry that were produced during the investigation. The first laboratory weld seams were conducted with a standard wire/flux combination for longitudinal weld seams (A, B).

The existing welding technology was modified and optimised by reducing the heat input of each pass. A low heat input welding procedure leads to a minimisation of the softening of the heat affected zone in combination with an improvement of its toughness. Especially combinations of current and voltage were examined to establish the optimum conditions for an adopted welding procedure.

The transverse weld tensile strength of these laboratory weld seams were tested. Some of the specimens were tested with the weld reinforcement removed. Independent from removing the weld reinforcement all specimens tested broke either in the weld metal or in the HAZ. **Table 5** illustrates the results that were reached within the laboratory investigation with different wire-flux combinations.

Pipe properties – longitudinal weld seam

The results of the laboratory investigation were successfully transferred to the pipe mill for the large-diameter pipe production. The main chemical composition of the submerged arc welds of the first prototype pipes is summarised in **Table 6**.

The strength of the seam weld was checked by means of flattened transverse weld specimens, with the weld reinforcement removed by machining as well as with the weld reinforcement not removed. The fracture positions do vary but in most of the cases the specimens failed in the heat affected zone. In contrast to the findings of the laboratory investigation the actual fracture initiation did not appear in the softened area of the HAZ but rather close to the fusion line. Low hardness values were found here due to a small area of decarburization. **Table 7** shows the hardness measurement in this decarborized zone near to the fusion line. Thus, all the tensile strength values measured reflect the strength of the base material and were above the specified minimum value of 931 MPa.

An example for the hardness distribution of the weld is given in **Figure 4**. As can be seen here all values of the hardness in the base metal as well as in the HAZ and the weld metal are below 350 HV10.

The strength of the weld metal was measured with tensile specimens that were taken from the longitudinal weld. The all-weld metal tensile properties, summarised in **Table 6**, confirm to the required tensile strength of the base material. However, the yield strength of the weld metal did not meet the required value for grade X120.

Figure 5 illustrates the toughness properties of the longitudinal weld seam. The notch location was 25/50/25. The target of 84 J at a testing temperature of –20 °C was not consistently met. Due to the high strength level, the toughness of the longitudinal weld seam and the HAZ is limited.

Pipe properties – base material

EUROPIPE produced pipes of 30” outer diameter with 16.1 mm wall thickness. With the intention to reach both the upper and the lower limit of a mass production in this trial plates with the highest as well as the lowest possible strength level were chosen on purpose for pipe forming. The highest possible level reached up to 100 MPa more than the target values. The lowest possible level was very close to the target values. This is an appropriate measure to mark out the boundaries for a new material.

Due to the ultra-high strength level of the plate material the pipe forming was actually one of the most challenging steps of the pipe production. The pipe forming was carried out in different ways that led to a variation in the peaking of the individual pipes after the O-forming. Some of the pipes failed during the expansion along the longitudinal seam weld especially in the case of the highest possible strength level and a not optimum peaking. But in most of the cases the pipe forming including the expansion of the pipes was successful.

The results of these first production tests for the base material of grade X120 are shown in **Tables 8 and 9**. Table 8 summarises the results of the ultra high strength variants. The strength values were determined using round bar and flat bar tensile specimens. For comparison the tensile properties were both measured in transverse and in longitudinal direction. In both directions the measured tensile strength values of both specimen types fully conformed to the specification requirements in all cases. The standard deviation for the yield and tensile strength values was very low. The yield strength measured in this case was $R_{p0.2}$ as for high strength steels like X120 the usually measured $R_{t0.5}$ results in values that do not seem to reflect the actual strength level. The use of $R_{t0.6}$ or even $R_{t0.65}$ instead of $R_{t0.5}$ appears to be more appropriate for high strength steels. Table 9 provides the results of the variants with the somewhat lower strength level. The tensile properties that were measured using transverse flat bar specimens as well safely met the target values.

As also given in **Tables 8 and 9**, the yield-to-tensile ratios are lower than 93 %. The A5 fracture and uniform elongation are lower than known for grades X80 to X100. Especially the uniform elongation of the ultra high strength variant showing values lower than 2 % appears to be one limitation for the pipe forming in particular and the production of pipes in grade X120 in general.

The toughness properties are provided in general in **Tables 8 and 9**. The Charpy impact energy values in particular are given in **Figure 6**. They were measured on Charpy V-notch impact specimens in a temperature range of -10 °C down to –70 °C. At a testing temperature of –30 °C the values resulted in an average of = 260 J. All individual Charpy toughness values were in excess of 231 J at this temperature.

The results of the Battelle Drop Weight Tear (BDWT) test led to transition temperatures to 75% shear fracture area of 0°C. In addition to the shear area, the specific energies for crack initiation and crack propagation during the BDWT test were measured. First results show that for X120 pipe material these energies are somewhat lower than for X100 pipes. In summary one can say that the results of the BDWT tests have to be improved in the next trial production.

3. Conclusion

After reaching grade X80 the next step in the development of high grade line pipe led to grade X 100 whose mechanical properties and crack arrest behaviour for certain pipe sizes were verified in full-scale burst tests /7/. The following stage of development recently led to the grade X120.

During this current development the technologies for heavy plate rolling and pipe production as well as the welding process for the longitudinal weld seam were modified or even completely new developed with respect to the new high strength steel grade X120. The main objectives of this development were the design of low Carbon, low PCM and VNbTiB microalloyed steel and the re-calculation of the main aspects of UOE-forming to optimise especially the U-forming step. Furthermore, a new welding consumables and a low heat input welding technology were developed.

A first prototype production of pipes in grade X120 led to some promising results with respect to the mechanical-technological properties, the weldability and the pipe forming. However, further optimisation of certain aspects is still necessary. Especially the pipe forming of X120 has not reached the stage of production safety yet, but specially designed tools may improve the pipe forming process. The toughness properties of weld metal and heat affected zone also do not meet the target values as the low heat input welding technology still needs further improvement. This could be achieved with modern welding tools. Furthermore, the results of the BDWT test need to be improved with respect to a possible crack arrest. Therefore, the use of crack arrestors is recommended. Further investigations are planned for the near future.

On the one hand recently published economic evaluations /2, 8/ highlighted that high pressure X 100 pipelines could give investment cost savings of about 7% compared with grade X 80 pipeline and cost savings of up to 30 % when X 70 and X 100 are compared. With the development of X120 linepipe further economic benefits in theory could now be realised by a reduction of total cost of long distance pipelines in the order of 5 to 15 %. On the other hand the reduction in the manufacturing cost per tonne of the pipe at a given transport capacity of a pipeline is enhanced not just by the increase in the material grade of the steel but also by the reduction in pipe wall thickness /1/.

At present the manufacturing cost per tonne of grade X120 material can only be specified on basis of the prototype production and with its production parameters. But a number of cost increasing aspects have to be taken into consideration. The alloying cost will be very high compared to standard high strength material. For a safe pipe forming new tools for the UOE-process have to be developed to reduce the danger of pipe failures during expansion. The welding with a low heat input appears to be mandatory but it also decreases the productivity in the pipe mill. As the range of wall thicknesses should be from 16 mm up to 20 mm this product could not be produced with enough flexibility. For a safe pipe line operation the use of crack arrestors will be necessary. A first roughly estimation of cost resulted in a price per tonne for X120 in the dimensions presented in this paper that is in excess of 250 US$ above the price for pipes in grade X70 with comparable dimensions. Therefore, from all these points of view further study and evaluation is needed to make an optimistic statement about the possible use of grade X120 in the near future.

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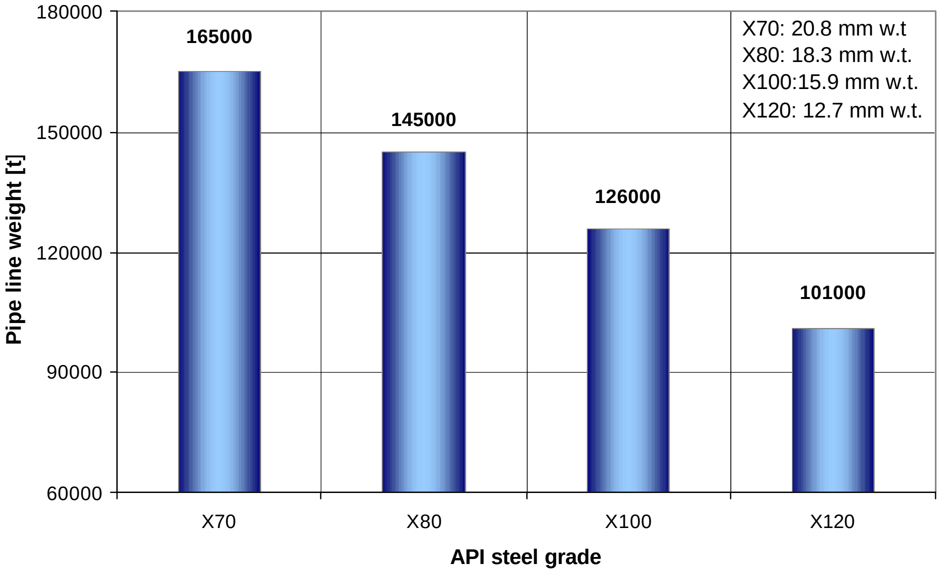


Figure 1: Material savings due to the use of high strength steel for a given pipe diameter

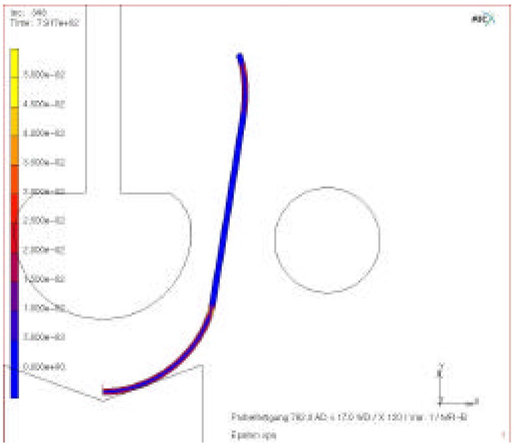


Figure 2: Spring back after U-ing with conventional U-ing punch

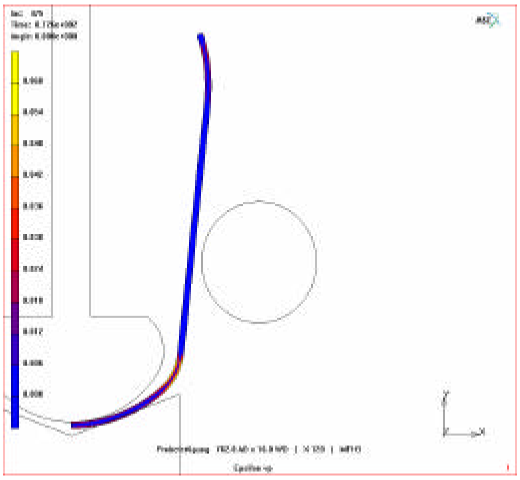
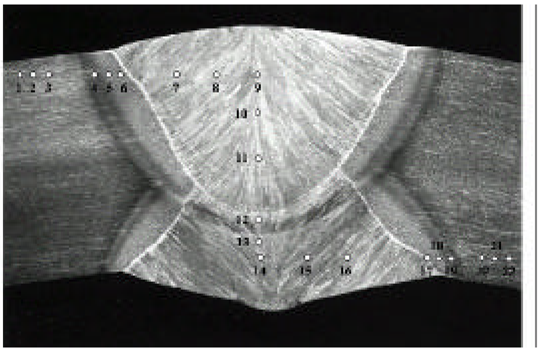


Figure 3: Shape of the modified U-Press tool



Spot marks	Hardness	Spot marks	Hardness
1	348	12	294
2	330	13	303
3	326	14	306
4	273	15	299
5	317	16	302
6	292	17	279
7	297	18	276
8	291	19	268
9	289	20	333
10	290	21	332
11	294	22	348

Figure 4: Distribution of Hardness HV10 (BM-HAZ-WM-HAZ-BM) of pipe grade X120

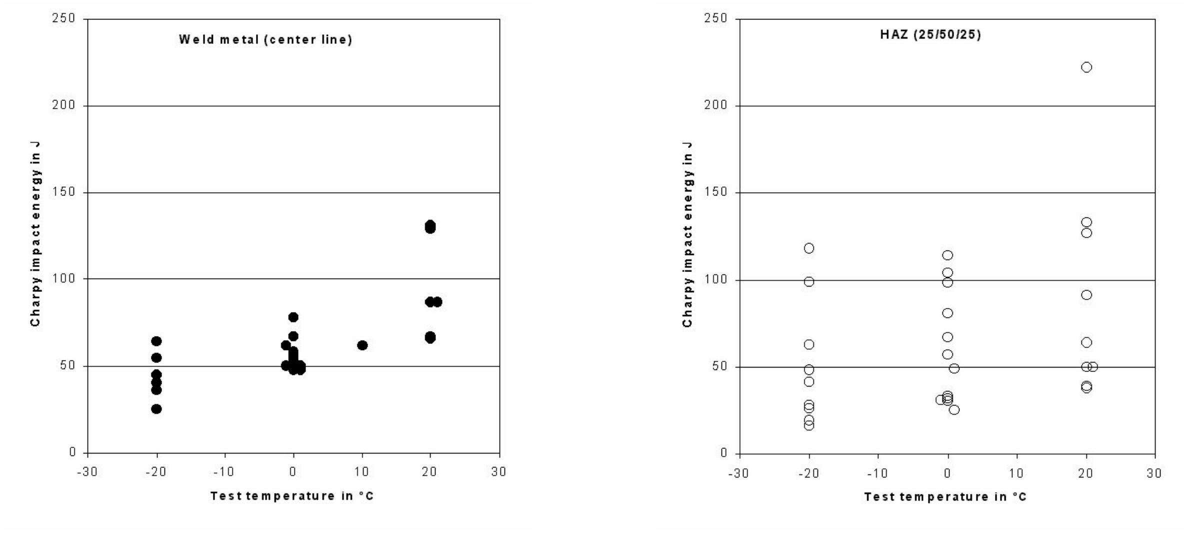


Figure 5: Charpy impact test results of weld metal and HAZ

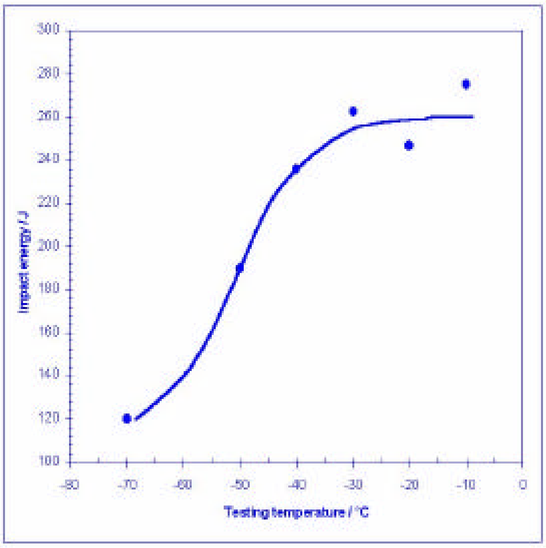


Figure 6: Charpy impact toughness of pipe base material

Table 1: Requirements on grade X120 and target of development /4, 5/

Parameter		**Value**
Yield strength		827 MPa
Tensile strength		931 MPa
CVN toughness	@ -30 °C	231 J
CTOD	@ -20 °C	0.14 mm
DBTT	<	-50°C
BDWTT	(SA%) @ -20 °C	75 %
Yield-to-tensile ratio		93 %
Wall thickness		16 mm

Table 2: Chemical composition of base material (weight-%)

C	**Si**	**Mn**	**Nb**	**Ti**	**N**	**P_{CM}**	**others**
0.06	0.23	1.91	0.042	0.017	0.004	0.23	Cu Ni Cr Mo V B

Table 3: Mechanical properties of X120 plate (round bar specimens)

Parameter		**Mean values transverse**
Yield strength	$R_{t0.5}$	843 MPa
Yield strength	$R_{p2.0}$	1087 MPa
Tensile strength	R_m	1128 MPa
Yield-to tensile ratio)	$R_{t0.5}/R_m$	75 %
Yield-to tensile ratio	$R_{p2.0}/R_m$	96 %
Elongation	A5	14.3 %
CVN toughness @ –30 °C		250 J

Table 4: Chemical composition of different weld metals

Wire / Flux-combination	**Pass**	**C**	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**P_{CM}**
C	Inside	0.06	0.30	1.93	0.98	1.57	0.83	0.33
	Outside	0.06	0.32	1.94	1.00	1.60	0.83	0.33
B	Inside	0.07	0.47	1.98	0.35	1.04	0.40	0.27
	Outside	0.07	0.50	2.01	0.35	1.12	0.41	0.28
A	Inside	0.05	0.26	1.95	0.21	0.22	0.52	0.25
	Outside	0.05	0.26	1.99	0.20	0.21	0.56	0.22

Table 5: Transverse weld tensile strength of different weld seams

Wire/Flux combination	**Tensile strength**	**Fracture position**
C	1024-1025 MPa	HAZ
	956-986 MPa	HAZ*
B	976-1013 MPa	HAZ
	914-918 MPa	WM*
A	860-865 MPa	HAZ
	777-779 MPa	WM*

* Weld reinforcement removed

Table 6: Main composition (mass-%) and mechanical properties of the weld metal of the two pass SAW weld of the X120 pipes

	C	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**CE_{PCM}**	**YS**	**TS**	**Y/T**	**El**	**CVN @ –20°C**
outside	0.06	0.29	1.88	0.9	1.3	0.82	0.32	780 MPa	941 MPa	83 %	18.5 %	64 J
inside	0.06	0.30	1.87	0.8	1.3	0.75	0.32					

Table 7: Distribution of Hardness in the decarborised zone (BM-HAZ-WM-HAZ-BM) of pipe grade X120

Location	Hardness HV 2
WM	301 / 311
HAZ decarburised	271 / 265
HAZ	296 / 295

Table 8: Mechanical properties of the ultra-high strength variants

Parameter		Target values	Mean values		Specimen
			Transverse	Longitudinal	
Yield strength	$Rp_{0.2}$	827 MPa	963 MPa	976 MPa	Round bar
Yield strength	$Rp_{0.2}$		966 MPa	961 MPa	Flat bar
Tensile strength	Rm	931 MPa	1139 MPa	1081 MPa	Round bar
Tensile strength	Rm		1150 MPa	1062 MPa	Flat bar
Yield-to-tensile ratio	$Rp_{0.2}$ / Rm	93 %	85 %	90 %	Round bar
Yield-to-tensile ratio	$Rp_{0.2}$ / Rm		85 %	90 %	Flat bar
Elongation	A5		13.1 %	15.5 %	Round bar
Elongation	A5		10.3 %	11.3 %	Flat bar
Elongation	Au		1.8 %	2.6 %	Round bar
Elongation	Au		1.5 %	1.3 %	Flat bar
CVN toughness	@ -30 °C	231 J	262 J		
DBTT		-50 °C	-60 °C		
BDWT	@ -20 °C	75 %	≥70 %		

Table 9: Mechanical properties of medium high strength variant (flat bar specimens)

Parameter		Target values	Mean values Transverse
Yield strength	$R_{p0.2}$	827 MPa	865 MPa
Tensile strength	Rm	931 MPa	944 MPa
Yield-to-tensile ratio	$Rp_{0.2}$ / Rm	<93 %	92 %
Elongation	A2”		24.3 %
Elongation	Au		7.4 %
CVN toughness	@ -30 °C	231 J	267 J
DBTT		<-50 °C	<-50 °C
BDWT	@ -20 °C	75 %	≥65 %

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