DEVELOPMENT AND WELDABILITY ASSESSMENT OF HEAVY GAUGE X80 LINEPIPE STEEL FOR SPIRAL WELDED PIPE

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Abstract

Today, ArcelorMittal is able to supply X80 coil skelp for spiral welded pipe complying with API-5L/ISO-3183:2007 PSL2 and BDWTT (Batelle Drop Weight Tear Testing) toughness in thickness up to 20 mm. The extension of the product range to higher thickness is ongoing. This paper summarises the state of the X80 heavy gauge (thickness above 18 mm) development at ArcelorMittal, as well as an extensive evaluation of the submerged arc weldability of this steel, using commercially produced X80 coiled material of 21.6 mm thickness. The weldability assessment proved that this steel is suitable for spiral pipe manufacturing, with very suitable tensile and toughness properties.

Introduction

The increasing demand for long distance gas transmission pipelines with large diameter and the trend towards higher operating pressures in these pipelines requires the use of larger wall thicknesses and higher strength steels. Until recently, high strength linepipe with wall thickness above 18 mm were commonly produced by UOE forming and longitudinally submerged arc welding (LSAW) of heavy plate; but this production route is quite expensive due to the discrete production of both plate and pipe. A more cost efficient alternative is given by spiral forming and submerged arc welding (SSAW) of hot rolled coil skelp. Hot rolling and spiral pipe production are both high productivity processes yet allow for reliable pipe properties. The ability of spiral welded pipes to arrest ductile running fracture is at least as good as that of LSAW pipe [1].

Thanks to the installation of heavy down coilers in three European hot strip mills and an accelerated development of dedicated metallurgical concepts, ArcelorMittal is now able to supply high strength linepipe steel on coil with thickness in excess of 20 mm [2, 3]. The weldability of the new steels is being assessed in order to guarantee optimum performance during pipe making and during service after pipe laying. The present paper summarises the state of the X80 heavy gauge (thickness above 18 mm) development at ArcelorMittal, as well as extensive evaluation of the submerged arc weldability of this steel, using commercially produced X80 coiled material of 21.6 mm thickness.

Development of X80

Building on the experience of producing high strength linepipe steel gained over many years at ArcelorMittal, a metallurgical concept was developed for X80 with thickness in excess of 18 mm. It concerns a typical Nb-microalloyed chemistry with a low carbon content, see Table I. Small Ti-additions are required to control grain growth, during slab reheating and hot strip processing as well as during welding when manufacturing the pipe. Hardening elements like Ni and Mo are necessary to adjust the strength level and to obtain a suitable microstructure providing sufficient toughness.

Table I. Chemical Composition of ArcelorMittal X80 Coil for Heavy Wall Thickness Spiral Pipe (wt. %)

C	Mn	P	S	Nb+V+Ti	Mo+Ni+Cr+Cu	Ceq (IIW)	Pcm
<0.06	>1.6	<0.02	<0.003	<0.15	>0.6	<0.44	<0.19

Typical microstructures obtained with this chemistry in industrial production of 21.6 mm thick coil are shown in Figure 1. Depending on the hot strip mill processing parameters, the microstructures consist of polygonal and quasi-polygonal ferrite with incorporated bainitic islands (Process 1), or predominantly granular bainitic ferrite without an incorporated second phase (Process 2). As documented in Table II and Figure 2, the different microstructures led to significant differences in mechanical properties. The polygonal microstructure obtained by Process 1 delivers a strength level corresponding to hardly more than X70 but provides excellent toughness, both in terms of the Charpy ductile-to-brittle-transition temperature (DBTT) and Battelle Drop Weight Tear Test (BDWTT) performance. Also, the BDWTT properties on pipe were found to be excellent at temperatures down to -10 °C, Figure 3. On the other hand, the bainitic microstructure obtained by Process 2 provides a very satisfactory X80 strength level but insufficient BDWTT properties.

The alloying concept and the hot strip processing are subject to continuous improvement in order to enlarge the X80 product offering for wall thickness above 20 mm with excellent toughness properties. Today, ArcelorMittal is able to supply coil skelp for spiral welded pipe complying with API-5L/ISO-3183 X80M PSL2 and BDWTT toughness in thickness up to 20 mm. In a recent trial, 48” OD spiral pipes were formed with a wall thickness of 1 inch (25.4 mm) leading to very satisfactory tensile properties (573 MPa yield strength, 759 MPa tensile strength) yet still marginal BDWTT toughness.

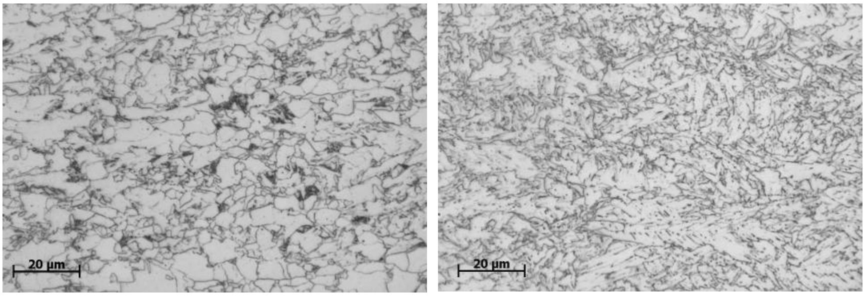

Figure 1. Typical microstructures of ArcelorMittal X80 coil with 21.6 mm thickness (quarter thickness position; etching Nital), depending on the process conditions.
Left: Process 1; Right: Process 2.

Table II. Mechanical Properties of 21.6 mm Thick X80 Coils (transverse direction) for Different Process Conditions (cf. microstructures Figure 1). Individual Values in Brackets

	Rt0.5 (MPa)	Rm (MPa)	Rt0.5/Rm	Au (%)	DBTT-CVN (°C)	BDWTT at 0 °C (%SA)	BDWTT at -10 °C (%SA)
Process 1	556	673	0.83	10.9	-101	98 (98/98)	94 (91/96)
Process 2	637	724	0.88	7.1	-72	67 (46/88)	36 (32/40)

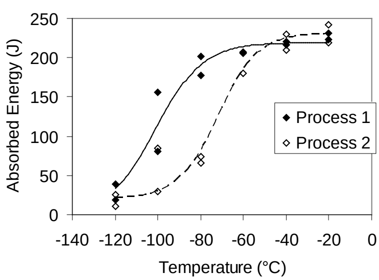

Figure 2. Charpy transition curves of 21.6 mm thick X80 coils (transverse direction) with different process conditions (cf. microstructures Figure 1).

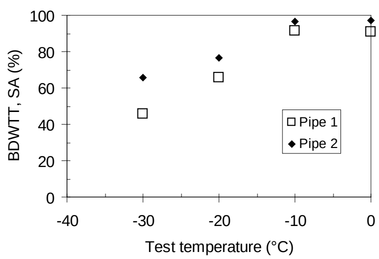

Figure 3. BDWTT properties obtained on pipe of 21.6 mm wall thickness (transverse direction); process 1 (cf. microstructures Figure 1).

Weldability Assessment

As can be seen in Table I, the Pcm carbon equivalent of the steel is below 0.25, ensuring good weldability in accordance with the API specification. For the subsequently described weldability assessment, hot rolled X80 coil of 21.6 mm thickness produced in the framework of a 6000t commercial order was used. The microstructure, Figure 4, was similar to that referred to as Process 2 in Figure 1; it consisted of a mixture of quasi-polygonal ferrite and globular bainitic ferrite, together with a homogeneous distribution of cementite. Martensite/austenite (MA) constituents were not detected.

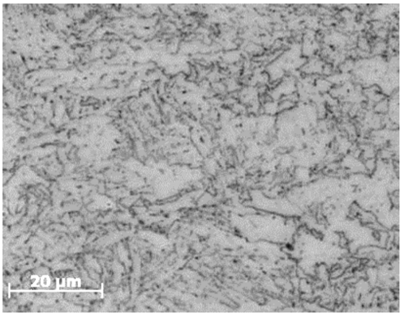

Figure 4. Microstructure of investigated 21.6 mm thick X80 coil (quarter thickness, etching Nital).

As a first step of the evaluation, a Continuous Cooling-Transformation (CCT) diagram was generated with a dilatometer using cylindrical specimens machined from the coil samples. The aim was to generate a map displaying the microstructure and hardness evolution of the Coarse Grained Heat Affected Zone (CGHAZ) at different cooling rates. Accordingly, the samples were re-austenitised briefly at a high peak temperature of 1350 °C. The resulting CCT diagram is shown in Figure 5 where the cooling rate is expressed as the cooling time between 800 °C and 500 °C ($t_{800/500}$). It can be seen that the hardenability of the steel is relatively low. The maximum hardness obtained with the fastest cooling rate was 320 HV, i.e. below 350 HV which is generally accepted as the maximum hardness in order to avoid cold cracking. At slow cooling rates starting from 15s cooling time, no martensite was observed in the microstructure, and ferrite was evident. That means that in the cooling range typical for SAW (higher than 15 to 20 s cooling time), the microstructure of the CGHAZ is expected to be predominantly ferritic.

The CGHAZ corresponds to the most heavily affected region in the HAZ since in this region the microstructure transforms to 100% austenite and significant grain growth may occur. Consequently, the toughness is generally expected to be significantly reduced such that the CGHAZ is considered as the most critical zone of the weld. In order to evaluate the toughness properties of the CGHAZ, a physical simulation was performed by means of annealing experiments in a Gleeble 1500/20 themo-mechanical simulator. Specimens with 11 mm x 11 mm cross section and a length of 90 mm were taken 2 mm below the surface of the coil samples and subjected to heating cycles corresponding to a weld heat input in the range from 3 to 4 kJ/mm which is typical for submerged arc welding. The specimens were heated up to 1350 ºC and cooled down to room temperature applying cooling times $t_{800/500}$ of 35 s and 50 s, respectively.

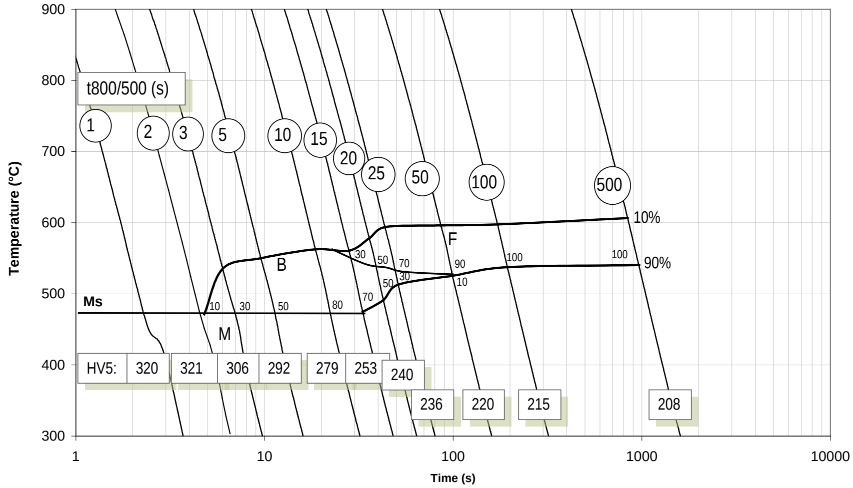

Figure 5. Dilatometry-generated CCT diagram representative of the CGHAZ (peak temperature 1350 °C).

The resulting microstructures in the CGHAZ were mainly bainite with small amounts of MA constituent. While the average grain size was comparable for both cooling times, the increase from 35 s to 50 s cooling time slightly decreased the amount of martensite, resulting in a marginally lower hardness, Table III. In both cases, the hardness of the simulated CGHAZ microstructure was still higher than that of the base material (240 HV).

Table III. Comparison of Average Grain Size, Amount of MA Constituent and Average Hardness of the CGHAZ Simulated Samples

$t_{800/500}$ cooling time (s)	Average grain size (µm)	Austenite vol. %	Martensite vol. %	Average Hardness (HV0.2)
35	70	1.3	1.9	273
50	71	1.5	1.3	262

The toughness of the CGHAZ simulated microstructures was evaluated by means of Charpy V-notch impact tests at -20 ºC and 0 ºC, Figure 6. The absorbed energy values recorded after 35 s cooling time were all above 27 J. In case of the samples produced with a cooling time of 50 s, one test value at -20 ºC was below 27 J, possibly due to the higher heat input.

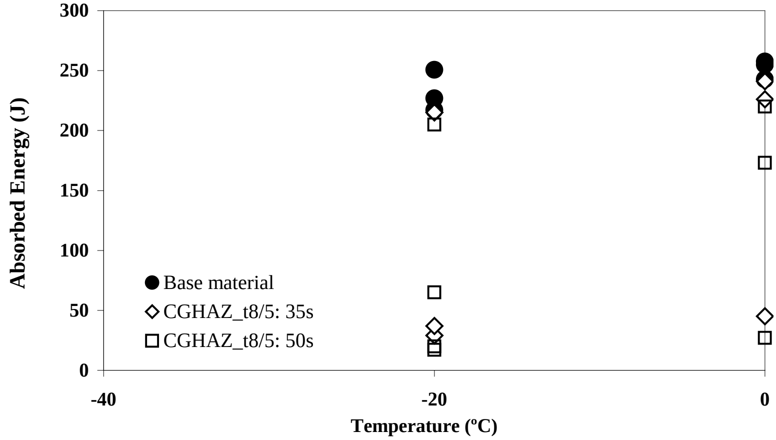

Figure 6. Results of the Charpy V-notch impact tests performed on the CGHAZ simulated samples.

The test result below 27 J at -20 °C was not considered critical, since notch locations in real weld and heat affected zone microstructures are quite different from specimens produced using Gleeble simulation. In the latter case, the CGHAZ is artificially enlarged so that it covers the whole area below the V-notch. On the other hand, when characterising real weld joints the area below the V-notch comprises different regions of the HAZ. For example, locating the notch at the fusion line (FL) implies a 50% contribution from the weld metal, suggesting a significant influence on toughness. At the notch location 2 mm away from the fusion line (FL+2 mm), the CGHAZ represents only a small fraction of the fracture surface while other parts of the HAZ will also influence – generally positively – the toughness result. (Fig 9 shows typical notch locations in a real weld).

For the last part of the weldability assessment, real submerged arc welds were produced, again using full thickness 21.6 mm coil samples. Submerged arc welding was performed using a DC-AC two-wire system for both the inside and outside passes; the welding conditions are listed in Table IV. Double-V joint preparation was used as shown in Figure 7. Solid wire (Ø 4 mm) containing Ti and B, Table V, and an aluminate flux with a low hydrogen level (EN 760: SA AB 1 67 AC H5) were used for these trials.

Table IV. Summary of Welding Parameters

Passes	Wire index	Polarity	Current (A)	Voltage (V)	Welding Speed (cm/min)	Combined Linear Heat Input (kJ/mm)
Inside	1	DC	880	34	80	4.2
	2	AC	700	38		
Outside	1	DC	1000	32		4.7
	2	AC	770	40		

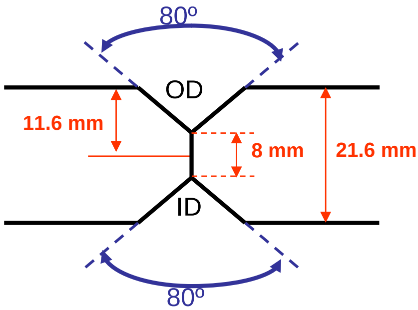

Figure 7. Joint preparation for submerged arc welding.

Table V. Chemical Composition of the Solid Wires Used (wt. %)

Designation (EN 756)	C	Mn	Si	P	S	Mo	Ti	B
SZ	0.07	1.2	0.3	< 0.015	< 0.015	0.2	0.16	0.013

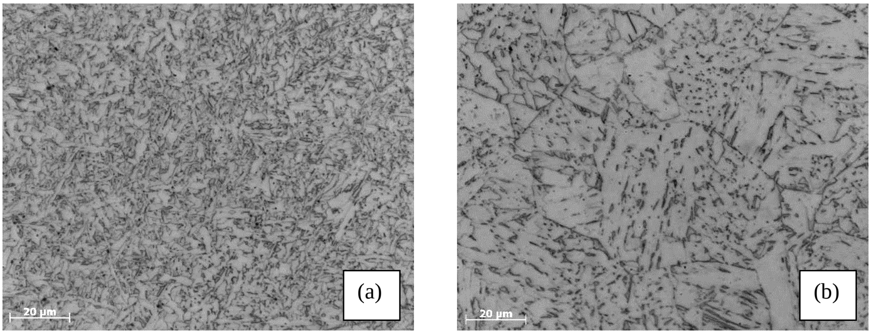

Figure 8. Microstructure of (a) weld metal and (b) CGHAZ (quarter thickness, etching in Nital).

The resulting microstructures of the weld metal and the CGHAZ are shown in Figure 8. The weld metal consisted of fine acicular ferrite with some quasi-polygonal ferrite. Titanium is known to form oxides which act as intragranular nucleation sites for the ferrite formation. Provided that it remains in solid solution in the austenite, Boron suppresses the formation of ferrite at the grain boundaries and, hence, promotes the formation of acicular ferrite, [4].

The microstructure of the heat affected zone (HAZ) evolved from predominantly bainitic ferrite close to the fusion line (CGHAZ) to a microstructure of quasi-polygonal ferrite and globular ferrite in regions close to the unaffected base material (Subcritical Heat Affected Zone – SCHAZ). The CGHAZ microstructure Figure 8(b),was composed of bainitic ferrite and globular bainitic ferrite with small amounts of martensite and residual austenite, Table VI.

Table VI. Quantification of MA Constituent in the CGHAZ

CGHAZ Position	Martensite vol. %	Austenite vol. %
¼ sheet thickness	0	2.5
Mid-thickness	0.8	2.1
¾ sheet thickness	0.03	0.9

Hardness scans across the weld, Figure 9, revealed a distinct hardening in the CGHAZ – which was in full agreement with the above described measurements in the simulated CGHAZ, cf. Table III. The weld metal had a lower hardness than the HAZ.

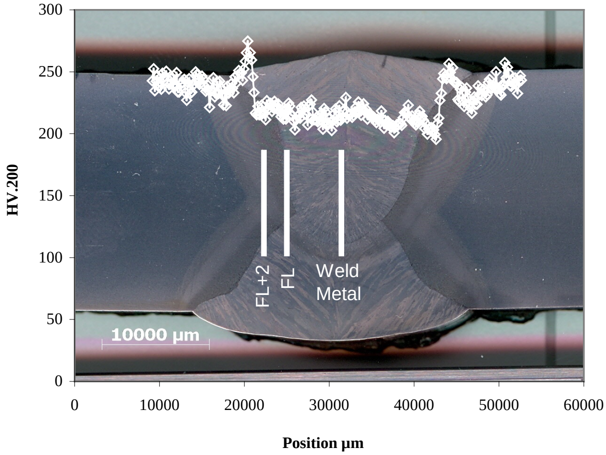

Figure 9. Macrograph of the SAW cross-section and hardness profile of the second pass on the OD (outside diameter) side. White lines indicate the positions of the V-notches of the Charpy impact samples.

The tensile strength of the weld was measured using API-specimens in the transverse direction. The minimum strength was determined as 728 MPa. Necking and failure occurred always in the base material which clearly indicates the overmatching strength in the weld metal.

The Charpy impact toughness of the weld was determined with samples taken from the mid-thickness of the sheet. The location of the notch was in the weld metal (WM), at the fusion line (FL) and in the HAZ at 2 mm distance from the fusion line (FL+2) as shown in Figure 9. The toughness results, Figure 10, were satisfactory; the highest absorbed energy values were found in the weld metal and the HAZ, whereas somewhat lower values were measured at the fusion line.

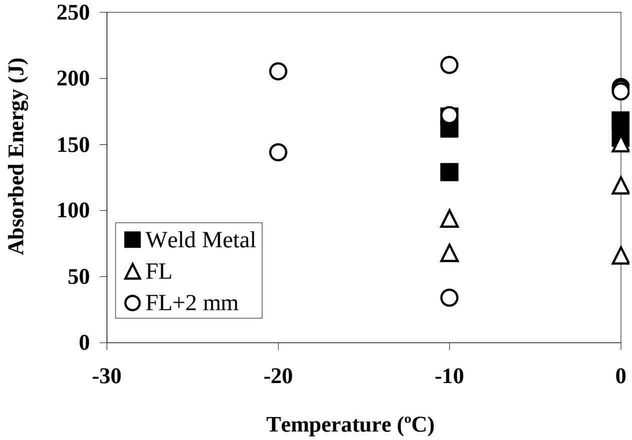

Figure 10. Results of the Charpy V-notch impact tests performed with notch locations: weld metal (WM), fusion line (FL) and 2 mm distance from fusion line (FL+2 mm).

The fracture toughness at the fusion line was also characterized by means of CTOD tests, using Single Edge Notch Bend (SENB) specimens with approximate dimensions of 21.6 mm (B) x 21.8 mm (W) x 270 mm (L). Placement of the notch with a depth of half of the specimen width was carried out as described in BS7448: Part 2. The tests were performed at -10 °C. The average result of three tests was approximately 0.25 mm, with a minimum value of 0.10 mm, Figure 11. This result is also considered satisfactory since EPRG recommends – based on a study correlating curved wide plate tests with CTOD tests – an average CTOD of 0.15 mm for matched or overmatched weld metals, with a minimum value of 0.10 mm [5]. Furthermore, deep notched SENB specimens are considered to have much higher constraints than those experienced in actual structures [6].

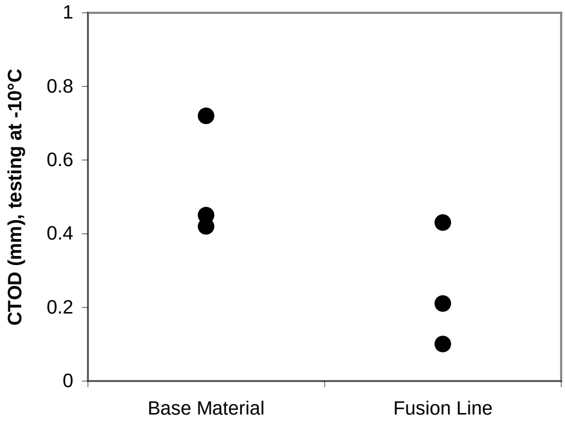

Figure 11. Comparison of CTOD results of base material and fusion line of submerged arc weld.

Conclusions

ArcelorMittal is able to supply X80 coil skelp for spiral welded pipe complying with API-5L/ISO-3183:2007 PSL2 and BDWTT requirement in thickness up to 20 mm. The extension of the product range to higher thickness is ongoing.

The present study describing the weldability assessment performed on commercially produced 21.6 mm X80 coil skelp proved that this steel is suitable for spiral pipe manufacturing. Tensile and toughness properties are satisfactory.

Acknowledgements

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