THE WELDABILITY OF LOW CARBON HIGH NIOBIUM STEELS DESIGNED FOR LINEPIPE AND GENERAL USE WITHIN THE HIPERC PROJECT

Stephen Webster

Consultant, UK

Keywords: Steel, Niobium, Linepipe, Structural, Properties, Welding

Abstract

The HIPERC study was a European research project involving several steel companies and research organisations which examined the effects of alloying elements and processing conditions in low carbon (< 0.09 wt%), niobium containing (0.05 - 0.12 wt.%) steels. Laboratory-scale heats and pilot rolling trials simulating air and water-cooled plate production, as well as hot-rolled strip production, were made and the effects of C, Mn, Ni, Cu, Cr, Mo, Nb, Ti and B on transformation characteristics and temperatures of recrystallisation determined. Regression equations for the characterisation of microstructure, tensile and impact properties and for the weldability of these steels were derived. Several full commercial casts were made and processed into plate and coil-plate by three steel companies and pipe was produced from both products. The weldability of all these products was assessed and full scale fracture tests carried out. The project has shown that excellent combinations of strength, toughness and weldability can be obtained for a wide variety of applications.

Introduction

The HIPERC project [1] was carried out over three years by ten European companies and organisations consisting of four steelmakers, five universities /research institutions and CBMM (Europe) with support from the European Research Fund for Coal and Steel (ERFCS). The project examined the fundamental principles of higher niobium steels in order to develop process-route / compositional combinations that established the suitability and limitations of this steel type for different market sectors. The project was coordinated by the Research and Development organisation of Corus UK Ltd (now Tata Steel UK) and the other steel companies were: Salzgitter Mannesmann Forschung GmbH, Germany; Ruukki, Finland and ArcelorMittal (OCAS), Belgium. The other industrial company was CBMM (Europe), the Netherlands, whilst the universities were: Gent University, Belgium, University of Maribor, Slovenia and Rheinisch Westfälische Technische Hochschule Aachen (RWTH), Germany. The research organisations were: Instytut Spawalnictwa, Poland and Centro de Estudios e Investigaciones Tecnicas de Gipuzkoa (CEIT), Spain.

The main objectives concerned the metallurgy of niobium-alloyed, low-carbon bainitic steels and their use in three particular product areas. They were:

- To determine composition - microstructure - property relationships for this type of steel.
- To define its limits for air cooled thick-walled pipe at the X60 to X70 strength level.

- To explore its exploitation for thinner-walled pipe made from hot-coiled plate. The strength levels aimed for were X70 to X100.
- To determine its applicability for use as a structural steel with a yield strength of 400 - 650 MPa.
- To carry out cost - benefit analyses for each product area concerned.
- To identify and justify appropriate changes to the Euronorms concerned.

The project consisted of five main tasks, three of them being associated with full scale steel processing. Such a comprehensive project cannot be fully reviewed in this paper however results from aspects of the project have been published elsewhere [2-5] and summaries of the overall project scope have been reported previously [6, 7].

Twenty-four laboratory casts were made to aimed compositions based on three separate experimental designs and processed using six rolling schedules to simulate the cooling of thick and thin products for both flat and coiled material. These conditions comprised reduction ratios below the no-recrystallisation temperature of 2 and 4, with finish rolling temperatures of 850 °C and cooling rates between 850 °C and 550 °C of 0.5 °C/s and 10 °C/s, followed by air cooling and 10 °C/s, and then by slow cooling at 30 °C/hr. These conditions were selected to simulate slow cooling conditions in heavy plate mills without accelerated cooling, faster cooling in heavy mills with accelerated cooling and in hot strip mills with coiling after rolling. A total of 144 variations in composition and processing conditions were produced and studied. CCT diagrams were determined using a dilatometer, recrystallisation temperatures using torsion tests and weldability using a thermal cycle simulator to examine the effect of two cooling rates after reheating to 1250 °C. Microstructures were evaluated using optical metallography plus the measurement of grain size using electron back-scattered diffraction (EBSD). Tensile properties and impact toughness transition temperatures were also measured.

Multiple regression analyses were carried out by analysing factors with a $p < 0.1$ where the p value is defined as (Mean Square Regression/Mean Square Error) to determine those factors with a high significance. The analyses were done using the ten elements controlled in the experimental design, namely C, Mn, Ni, Cu, Mo, Cr, Cu, Nb, Ti and B and the processing factors of $\log_{10}$CR1, where CR1 is the cooling rate between 850 °C and 550 °C, $\log_{10}$CR2, where CR2 is the cooling rate between 550 °C and 20 °C, the rolling reduction below the no-recrystallisation temperature, RR, and the finish cooling temperature, T_{FC}. The resulting algorithms were validated by predicting the properties of six other steels; two laboratory casts which were outside their aim compositions and material from four commercially produced casts processed in the laboratory using the same rolling conditions. These were known as the ‘validation casts’. The conclusions are summarised in [7] whilst the full information is contained in [1].

In addition to laboratory welding simulations, full scale welds were made using several processes: submerged arc, reduced pressure power beam, autogenous laser and hybrid laser/MAG. Fracture toughness tests were carried out on some of these welds and curved wide plate tests on some of the pipe products manufactured from the full scale commercial casts. The present paper concentrates on the weldability studies carried out within the project but also includes relevant information obtained after the completion of the project on steels made within the project.

Welding Simulation - Experimental Casts

This work was carried out by the Instytut Spawalnictwa, Poland with testing support from the University of Maribor and the University of Gent. Laboratory scale simulation of the weld HAZ was carried out using a thermal cycle simulator to examine the effect of cooling rate. The samples were reheated to 1250 °C and cooled at controlled times of 8 and 30 seconds through the temperature range 800 - 500 °C. The time taken through this temperature range is referred to as $t_{8/5}$ and its effect on the impact toughness and hardness was assessed [4]. Charpy V notch impact data and hardness measurements were obtained for 24 of the experimental steel compositions, for both parent and simulated HAZ material. These were used to determine transition temperatures and ultimately regression equations for both hardness and transition temperature.

The regression equations derived for the various parameters were:

Parent metal hardness, HV5	= 13 + 27000B + 1020C + 50Mo + 60Mn + 50Ni
HAZ hardness, HV5	= 25 + 18000B + 1360C + 270Nb + 60Mo + 46Mn + 34Cr + 30logCR$_{8/5}$
27 J ITT, ^{o}C	= 10 - 45Ni - 40Mn - 30Cr
0.5 Kvmax ITT, ^{o}C	= 0.8 + 480C - 45Ni - 30Mn (Kvmax is maximum energy or upper shelf)

Comparison with the validation casts for the hardness values is given in Figure 1 and those for the transition temperatures in Figure 2.

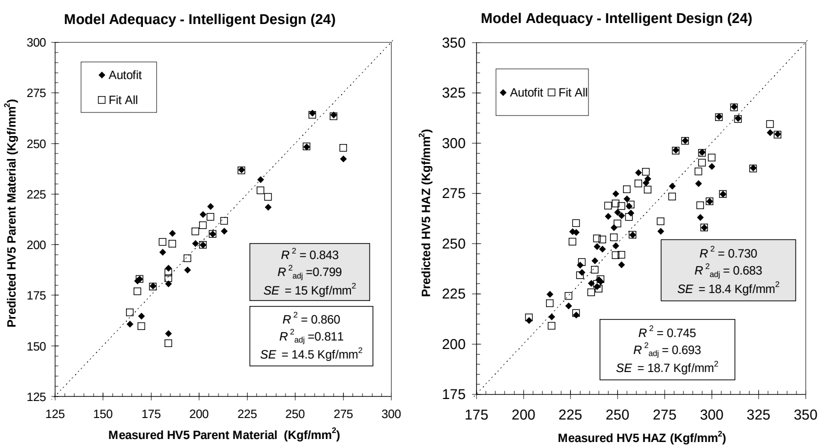


Figure 1. Experimental vs. predicted values for parent material and HAZ hardness.

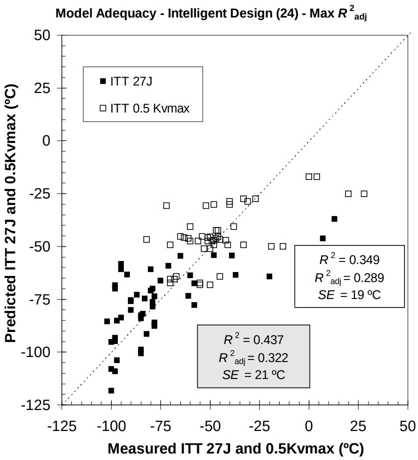


Figure 2. Experimental vs. predicted values for HAZ transition temperatures.

As would be expected the hardness values measured were dictated by the boron and carbon content of the steels. The predictions from the regression equations are quite good and show that Nb does have a role in the level of the HAZ hardness, being the third most influential element. However Nb was not a significant factor in the derivation of Charpy Impact transition temperatures. The coefficient obtained for Nb was negative indicating that it is not detrimental to HAZ toughness, but the result was not statistically significant. The scatter shown in Figure 2 is quite high but the equations do seem to predict the general trend.

In addition to these basic studies using simulated HAZ structures created from the experimental casts, welding data were obtained in the three tasks concerned with thick wall linepipe, spiral welded pipe and structural steels. The majority of these data were derived from full scale products manufactured from commercial scale steel casts and welded using a variety of industrial welding techniques.

Weldability of Thick – Walled Pipe and Structural Steels

The principal objective of these studies was to determine the properties that could be obtained in plates processed using controlled rolling but then air-cooled. Plates of 14.6 mm, 20.9 mm and 25.4 mm thickness were rolled on the Tata Steel plate mill at Scunthorpe, UK and processed to pipe using the UOE forming method at the Hartlepool Pipe Mill. The pipes from the 14.6 mm plate had an outer diameter (OD) of 610 mm and the others 914 mm. In addition plates of 20 mm and 50 mm thickness were produced using minimal controlled rolling to explore the potential of the steel type as a lower cost alternative to conventional structural steels.

All of the plates were produced from the same cast (81913), which had the analysis shown in Table I.

Table I. Chemical Composition of Cast 81913

C	**Si**	**Mn**	**P**	**S**	**Al**	**Nb**	**V**	**Cu**
0.053	0.18	1.59	0.013	0.0038	0.037	0.097	0.001	0.23
Cr	**Ni**	**N**	**Mo**	**Ti**	**Ca**	**B**	**Pcm**	**CEV**
0.26	0.17	0.006	0.002	0.016	0.0013	-	0.17	0.40

The measured tensile, impact and drop weight tear test properties of the plates processed into pipe, together with the corresponding pipe properties, are shown in Table II. Elongation, A, values from the plates are for a 200 mm gauge length while those for pipe are for a 50 mm gauge length.

Table II. Mechanical Properties of Commercially Processed Plates and Pipes

Product	**t mm**	**RR**	**FRT °C**	**$R_{t0.5}$ MPa**	**R_m MPa**	**A %**	**R_t / R_m**	**27 J TT °C**	**0.5Kvmax TT °C**	**DWT T °C**
Plate	14.6	3.7	775	439	533	26	0.82	-110	-90	-60
Plate	20.9	4.1	708	533	592	18	0.90	-100	-85	-40
Plate	25.4	3.1	720	479	541	18	0.89		-85	
Plate	25.4	3.1	715	512	581	23	0.88	-90	-75	-10
Plate	25.4	4.1	712	496	543	22	0.91	-140	-140	-35
Pipe	14.6			564	579	41	0.97	-110	-90	-60
Pipe	20.9			513	611	44	0.84	-100	-85	-45
Pipe	25.4			478	554	51	0.86			
Pipe	25.4			488	586	45	0.83	-90	-75	-15

Air cooling with a low FRT allowed pipes of X70 strength to be manufactured up to about 21 mm in thickness with the results being marginal at 25 mm. The impact transition and DWTT transition data showed that there was little effect of the pipe forming operation on the transition temperatures.

The mechanical properties of the plates rolled for structural use are summarised in Table III. Tensile, Charpy impact and drop weight tear tests were carried out on the plates and toughness transition temperatures determined. DWTT is not a requirement of Euronorms relevant to structural use, but the information was of interest to determine the effect of lower levels of controlled rolling on this test parameter.

Table III. Mechanical Properties of Structural Plates Rolled from Cast 81913

Plate Thickness	$R_{p0.2}$ MPa	R_m MPa	A %	R_p/R_m	0.5Kvmax TT °C	27 J TT °C	DWTT TT °C
20 mm	484	540	25	0.89	-90	-130	-40
50 mm	410	521	21	0.79	-70	-110	-20

The strength requirements in EN 10025-4: 2004 are dependent on plate thickness; the properties in Table III satisfy S420ML in the 50 mm thickness and S460ML in the 20mm thickness.

Considering the low level of controlled rolling in both of these plates, good strength and excellent toughness were obtained.

A limited amount of fracture toughness testing to BS 7448 was carried out to determine a crack tip opening displacement, CTOD, transition curve for specimens taken from one of the 25.4 mm thick pipe plates and results for two crack orientations are shown in Figure 3. For the lowest toughness orientation, the transverse crack direction, the CTOD data suggests that a 0.25 mm value will still be obtained below -50 °C.

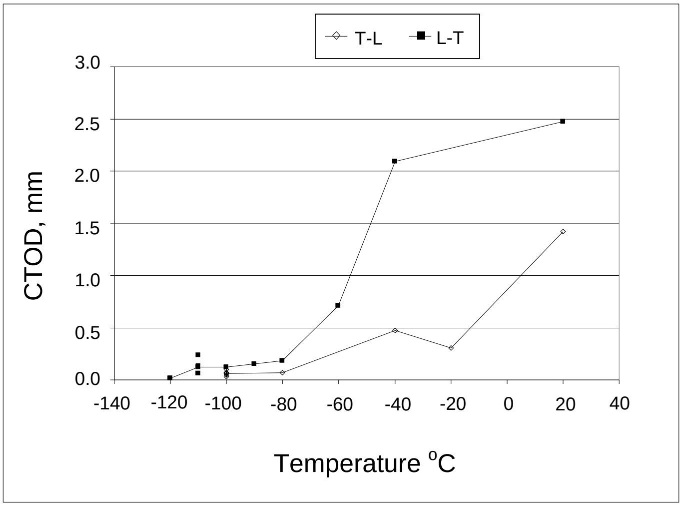


Figure 3. CTOD transition curve for 25.4 mm thick plate.

Weld thermal simulation of the grain coarsened HAZ was also carried out by reheating to 1250 °C but this was followed by controlled cooling through the range 800 – 500 °C using several cooling rates. The impact energy absorbed at +20 °C and -40 °C for each condition was measured along with the hardness of the microstructure and these results are summarised in Figures 4 and 5. At +20 °C the impact energy of the simulated HAZ is similar to the parent plate until the $t_{8/5}$ cooling time is above 120 sec whilst at -40 °C over 100 J was measured up to a cooling time of above 24 sec. Both of these cooling rates are slower than would be expected from industrial welding processes, suggesting that the HAZ toughness of the steel is quite acceptable.

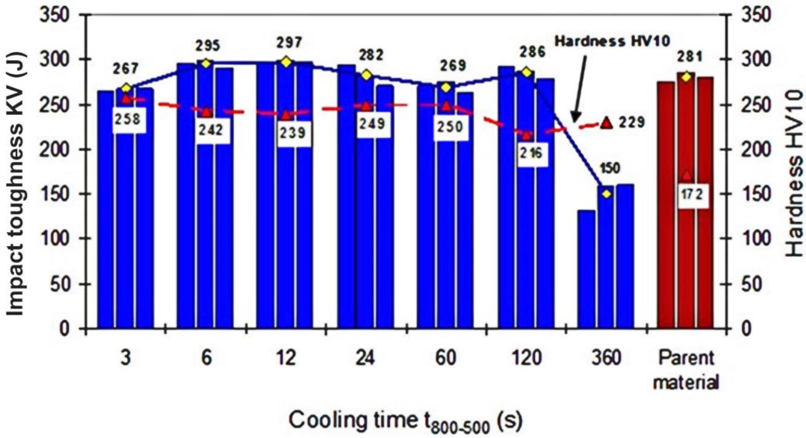


Figure 4. Toughness and hardness of simulated grain coarsened HAZ microstructures at 20 °C [4].

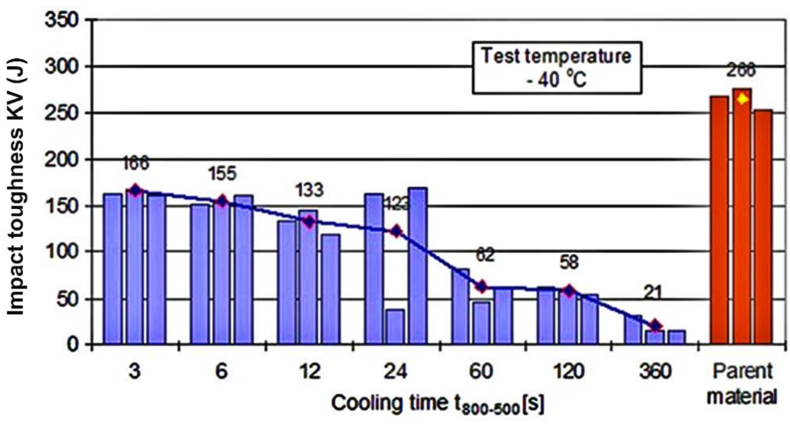
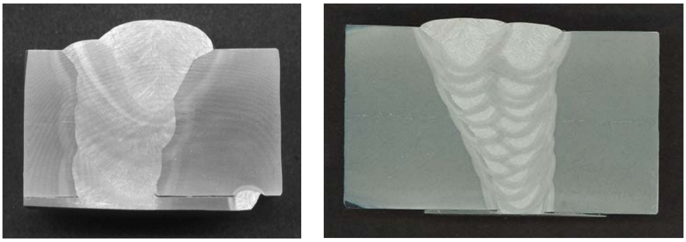


Figure 5. Toughness and hardness of simulated grain coarsened HAZ microstructures at -40 °C [4].

Welding using full thickness plates was carried out using submerged arc, SAW, reduced pressure electron beam, RPEB, autogenous laser welding and hybrid laser / MAG processes, and the properties of the welds assessed by determination of Charpy impact transition curves for different notch locations. The results are compared with conventional S355 EMZ and S450 EMZ grade welds in the following figures. Butt welds were made in a 25.4 mm thick pipe plate and a 50 mm thick structural steel plate using submerged arc welding. The 25.4 mm plate was welded in 5 passes with a heat input of 4.5 kJ/mm and the 50 mm thick plate was welded in 21 passes with a heat input of 3.5 kJ/mm. Macrographs of the two welds are shown in Figure 6.



(a) 25.4 mm thick plate (b) 50 mm thick plate

Figure 6. Macrographs of submerged arc welds.

The Charpy impact results obtained are given in Figure 7a for the fusion line location and Figure 7b for the fusion line + 5 mm location. Tests were only carried out at the mid – thickness of the 25.4 mm thick plate but at the top, middle and bottom of the 50 mm thick plate.

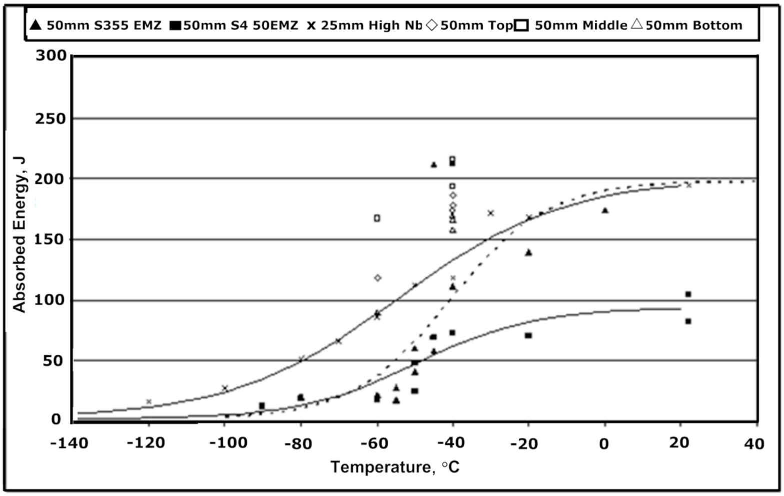


Figure 7a. Charpy impact transition curves for submerged arc welds – notch at fusion line.

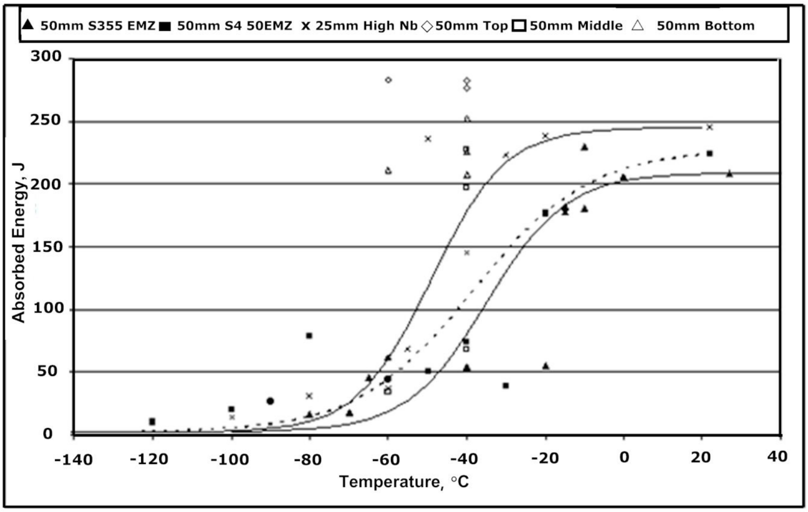


Figure 7b. Charpy impact transition curves for submerged arc welds – notch in HAZ and at fusion line +5mm.

The transition curves showed that the higher-Nb steel had lower transition temperatures than both the conventional S355 EMZ and S450 EMZ steels.

Reduced pressure electron beam welding was performed to make a butt-weld in the 25.4 mm thickness plate using an electron gun having a power up to 100 kW at a pressure of 10^{-5}-10^{-2} mbar. The weld macrograph is shown in Figure 8 and the results in Figure 9 where they are also compared with similar welds made on 50 mm thick S355 and S450 plates. It can be seen that the Nb steel had a much lower transition temperature.

Figure 8. RPEB weld in 25 mm thick plate.

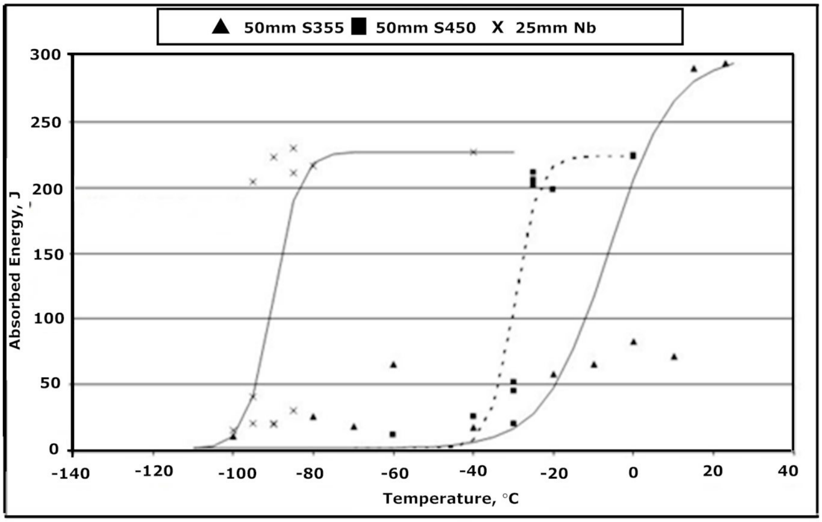
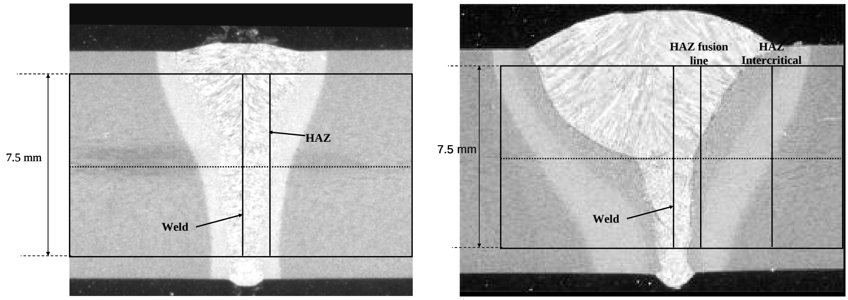


Figure 9. Impact transition curves for reduced pressure electron beam welds at fusion line + 0.5 mm.

Samples were machined from the 25.4 mm plate to obtain 9 mm thick plates and these were used to produce an autogenous laser bead-on-plate weld and a hybrid laser / MAG butt-weld. The notch locations for the subsize Charpy specimens are shown in Figure 10.



(a) autogenous laser (b) hybrid laser / MAG weld

Figure 10. Notch locations in subsize Charpy specimens for 9 mm thick laser and hybrid welds.

The impact transition curves are contained in Figures 11 and 12 (subsize Charpy data uncorrected for specimen size). The transition temperature results for the autogenous weld are relatively poor (high transition temperature) but those for the hybrid weld are encouraging and it is this process which is the more practical welding method for thicker section steels. Charpy impact data from simulated welds was also obtained and Figure 13 compares these data with the results from 'real' welds. It can be seen that the simulated data tend to be lower than those from real welds, which is a common observation and reinforces that simulated data should be used with care.

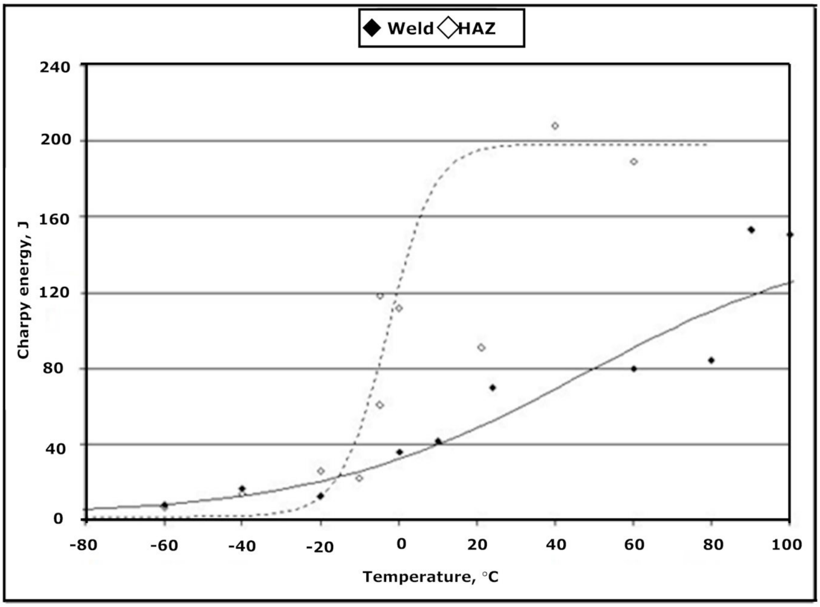


Figure 11. Charpy transition data for weld and HAZ - Autogenous laser weld
7.5mm subsize Charpy specimens.

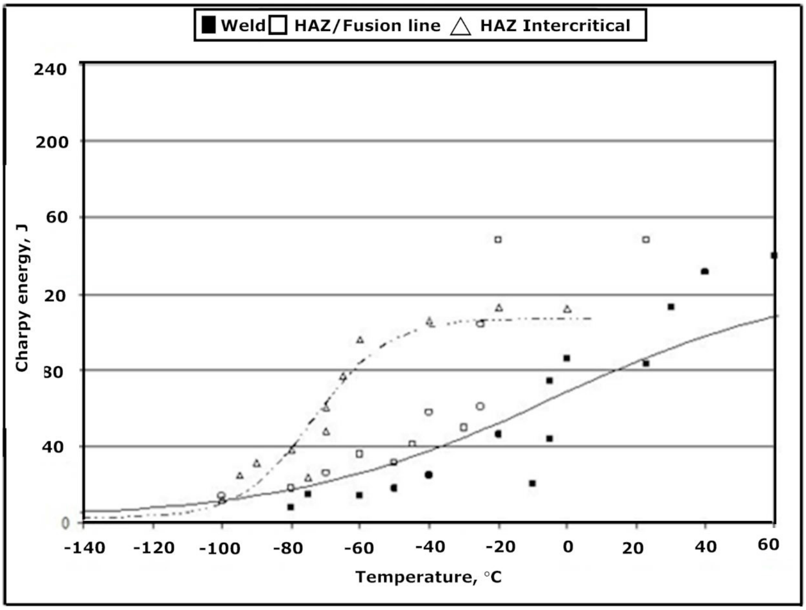


Figure 12. Charpy transition data for weld and HAZ - hybrid laser / MAG weld
7.5 mm subsize Charpy specimens.

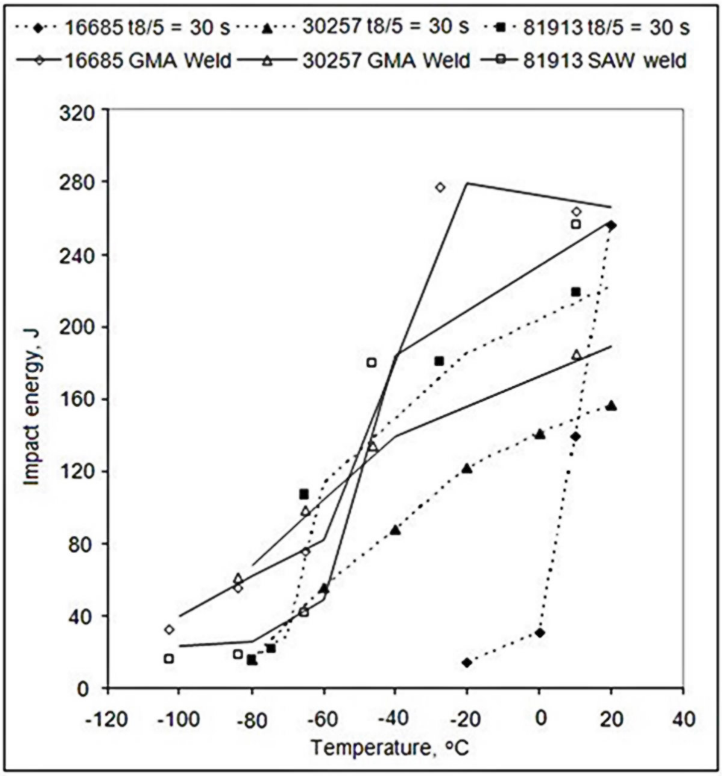


Figure 13. Comparison of impact transition curves for real and simulated welds.

Following the completion of the project some additional testing was carried out using 20.9 mm thick plates rolled for pipe manufacture, see Table II. This work was funded by CBMM and involved welding of the plates by Airliquide, Germany, using a double V pipe welding procedure typical of longitudinal seam welds in UOE pipe. Testing was then carried out by CSM, Italy [9] and this included Charpy impact and CTOD testing of the welded joint. The Charpy data obtained for the tests carried out at 0 ^{o}C and -20 ^{o}C are shown in Figure 14. The lowest values measured were for the fusion line at -20 ^{o}C but even these have an average value of 86 J which is above the normal acceptance level of 40 J.

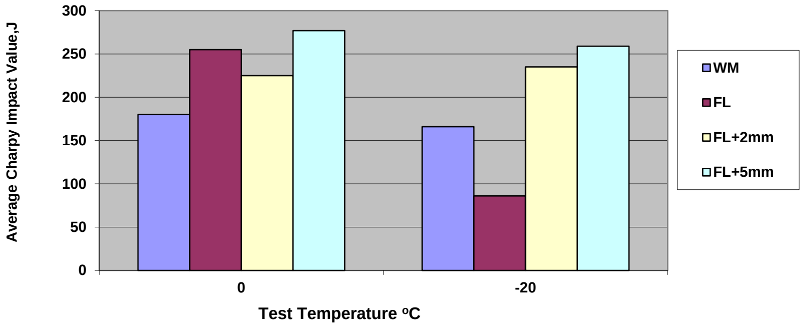


Figure 14. Average Charpy impact values from pipe seam weld.

The crack tip opening displacement (CTOD) data obtained are listed in Table IV. The tests were carried out using single edge notch bend (SENB) specimens of essentially full plate thickness with the fatigue crack sampling approximately 50% weld metal and 50% HAZ. Three test temperatures were used; 0 ^{o}C, -10 ^{o}C and -20 ^{o}C and the tests were performed using the unloading compliance technique, in order that crack extension prior to final failure could be determined. Even at -20 ^{o}C the CTOD data have an average value of about 0.5 mm which is comfortably higher than the commonly used acceptance level of 0.25 mm.

Table IV. CTOD Data from Pipe Seam Weld

Temperature,^{o}C	**CTOD, mm**
0	1.74
0	1.33
0	1.08
0	0.96
-10	0.88
-10	0.64
-20	0.59
-20	0.51

Pipe Manufactured From Hot – Coiled Plate

The aim of this work was to explore the potential of the low carbon, higher Nb steel for X70 – X80 grade strength pipe manufactured from coiled plate. The principal objective was to develop high strength linepipe steel more cost effectively and with more reliability of mechanical properties compared to ferritic-pearlitic materials. Three trial heats were made by Ruukki and these were rolled to 14 coils whilst two casts were produced by Salzgitter, resulting in 12 coils. One slab from each company was exchanged and hot-rolled by the other's mill. All of the steel rolled at Ruukki was processed to spiral pipes on the Oulainen pipe mill while those hot-rolled in

Salzgitter were either processed to spiral pipes at Salzgitter Großrohr or to longitudinal welded HFI-pipes at Salzgitter Mannesmann Linepipe.

The full range of cast compositions studied is given in Table V. The aim was to achieve pipe steels with different strength levels but all containing a partly bainitic microstructure. Carbon was kept below 0.05% whilst niobium was varied up to a level of 0.10% to promote the formation of bainite during cooling and to increase the recrystallisation stop temperature. 1% of Chromium was added in one cast to retard transformation and enable bainite formation during cooling and boron was used in another for a similar purpose.

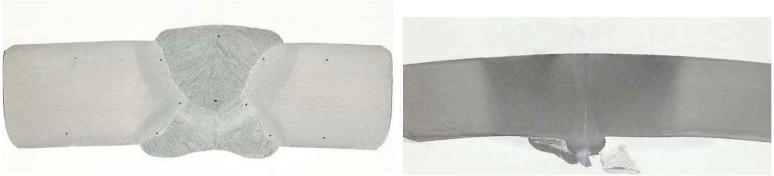
A range of rolling schedules was used with the variations being in soaking temperature, rolling rates, hold and coiling temperatures. Strip thicknesses of 10, 12, 14 and 16 mm were produced. A full presentation of the data for one of the 14 mm coils processed to an X70 grade, together with a description of the processing methodology and conditions is given in reference [5] and information for all of the trials is in reference [1]. Only a summary of the results pertinent to welds are contained in this paper.

Table V. Compositions of Casts Used to Produce Hot Rolled Coils (wt%)

Cast	C	Si	Mn	P	S	Al	Nb	V	Cu	
1	0.043	0.20	1.96	0.007	0.0009	0.027	0.104	0.008	0.21	
2	0.033	0.22	1.82	0.005	0.0015	0.027	0.052	0.004	0.02	
3	0.042	0.30	1.81	0.006	0.0024	0.036	0.056	0.009	0.21	
4	0.040	0.20	1.49	0.012	0.0040	0.031	0.068	0.005	0.49	
5	0.050	0.32	1.75	0.009	0.0010	0.030	0.098	0.005	0.04	
	Cr	Ni	Ce	N	Mo	Ti	Ca	B	Pcm	CEV
1	1.01	0.22	0.003	0.0075	0.000	0.014	0.0018	0.0003	0.22	0.64
2	0.21	0.05	0.006	0.0070	0.003	0.013	0.0026	0.0003	0.14	0.38
3	0.21	0.20	0.007	0.0061	0.001	0.013	0.0019	0.0003	0.17	0.37
4	0.04	0.41	0.003	0.0046	0.008	0.014	0.0013	0.0019	0.16	0.35
5	0.27	0.04		0.0070	0.070	0.020	0.0012	0.0001	0.174	0.42

Mechanical Properties of Spiral SAW and Longitudinal HFI-Welds

Typical weld profiles obtained for the pipes are shown in Figure 15.



(a) (b)

Figure 15. Typical weld macrostructures for (a) spiral and (b) HFI pipe.

Tensile test results for the spiral-welded pipes are shown in Table VI. The majority of cross weld failures were in the base steel, suggesting that the weld strength overmatch obtained from the welding procedures used was satisfactory in those cases. The results for the HFI-pipes are given in Table VII from where it can be seen that the tensile strength of both HFI-welds was good but the fracture location was in the welded area.

Table VI. Cross and All Weld Tensile Properties for Spiral-Welds

Plate Thickness mm	Grade Approx.	Cross-weld			All Weld Metal		
		$R_{t0.5}$ MPa	R_m MPa	Fracture Position	$R_{p0.2}$ MPa	R_m MPa	A %
10	X70	637	796	FL	669	823	18
10	X85	590	752	FL	633	784	19
16	X65	519	615	Base	543	614	22
12	X65	526	610	Base	553	638	25
12	X65	538	624	Base	544	615	21
14	X65	554	650	Base	-	736	22
14	X65	518	618	Base	594	690	25
14	X65	538	639	Base	611	708	23
14	X65	536	639	Base	572	656	25
14	X65	538	630	Base	589	681	24
14	X65	560	659	Base	589	681	24
14.1	X75	568	667	Weld	-	-	-
14.1	X60	549	652	Base	-	-	-
14.1	X75	645	712	Base	-	-	-
14.1	X75	657	718	Base	-	-	-

Table VII. Cross Weld Tensile Properties for HFI-Welds

Plate Thickness mm	Coiling Temp. (local) °C	Grade Approx.	Cross-weld		
			$R_{p0.2}$ MPa	R_m MPa	Fracture Position
11	560	X80	633	735	Weld
11	420	X85		754	Weld

A substantial amount of Charpy Impact testing has been carried out on the pipes formed and this has included varying the welding conditions used to manufacture the pipes. Tables VIII and IX contain some of these data to illustrate the values obtained.

The welding speed was varied in these two pipes and although the results were good at -20 °C for all notch positions, one fusion line notched-sample tested at -40 °C showed a low energy value.

Table VIII. Cross Weld Charpy Impact Toughness for Spiral-Welds (Salzgitter)

t mm	Coiling temp. (local) °C	Grade	Notch position	Cross-weld toughness J	
				-20 °C	-40 °C
14.1	460	X75	Weld	104	71
			FL	170	194
			FL+2 mm	240	241
			FL+5 mm	250	247
			Base	302	303
14.1	480	X75	Weld	70	74
			FL	106	36
			FL+2 mm	197	76
			FL+5 mm	249	232
			Base	202	187

Table IX. Cross Weld Charpy Impact Toughness for HFI-Weld (Salzgitter)

t mm	CT (local) °C	Grade	Notch position	Cross-weld toughness J	
				-20 °C	-40 °C
11	560	X80	Weld	77	59
			FL+2 mm	109	99
			Base	161	157

The impact toughness of the HFI pipe was similar to the results obtained for the spiral-welded pipes.

Wide Plate Testing of Girth Weld

A girth weld was made using a 14.1 mm thick, 1067 mm diameter spiral welded pipe, manufactured from the cast 5 composition in Table V. The welding procedure was designed to produce girth welds with a level of weld metal yield strength overmatching of between 5 and 10% relative to the parent pipe material, measured in the longitudinal direction. The pipe weld was made using a V-shape preparation, with a nominal angle of 60° and a root opening of 1 mm. The girth weld was made by manual gas-shielded flux cored arc welding, FCAW and the filler material was Lincoln Outershield 550-H with a wire thickness of 1.2 mm. The maximum heat input used was less than 2 kJ/mm. The pipe coupons were welded initially from the inside and subsequently four additional layers were added from the outside. The entire weld material therefore consisted of the same yield strength electrode.

Wide plate testing was carried out by Gent University, Belgium. The specimens were extracted by flame cutting in the axial (longitudinal) direction, Figure 16. These specimens had nominal dimensions for the overall width (arc length) of 400 mm and length of 1200 mm, with the weld at the mid-length. After flame cutting, the longitudinal edges within the test section were machined straight and parallel to each other and to a width (arc length) of nominally 300 mm and a length of 900 mm, with the weld at mid-length, Figure 17.

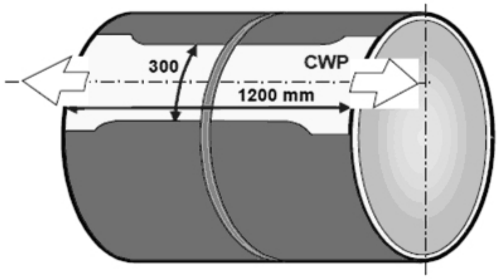


Figure 16. Curved wide plate extracted from a large diameter pipe in the axial direction.

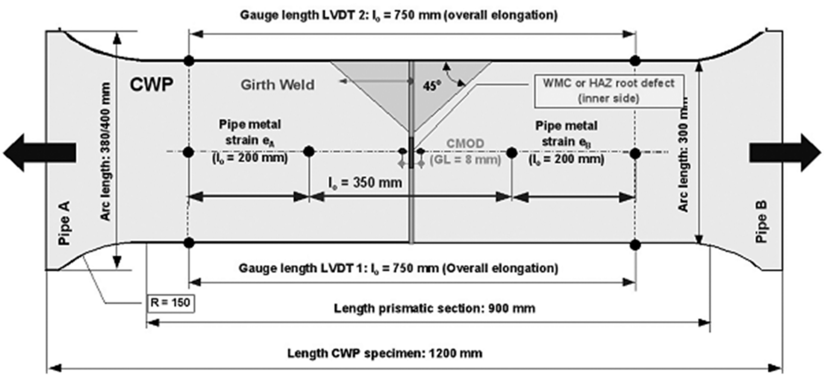


Figure 17. Curved wide plate specimen dimensions and instrumentation.

The pipe sections were not flattened, that is the curvature was retained, and the weld reinforcements were not removed, except at the location where the surface breaking root defect was to be introduced. At this location the root overfill was ground flush with the surfaces and sharp, surface breaking notches were introduced using a cutting wheel with a diameter of 63 mm and a blade thickness of 0.15 mm to provide a defect depth of 3.0 mm and a length of 50 mm. Prior to notching the weld root was locally ground, polished and macro etched in 5% Nital to allow two of the wide plate specimens to be notched in the heat affected zone at the weld root, whilst the third specimen was notched on the root weld metal centreline. The performance of the curved wide plate test samples was assessed in terms of the Gross Section Yielding (GSY) concept, which requires that remote pipe yielding (i.e. a longitudinal strain higher than 0.5%) should precede girth weld failure [8].

Tensile properties were measured using full thickness (25 mm wide) prismatic tensile test samples extracted in the longitudinal direction from the pipe metal and 6 mm diameter all-weld metal samples. A summary of the measured strength properties (average and extreme values of 6 tests) is given in Table X for both the pipe material and weld metal.

Table X. Tensile Properties

	Pipe					Weld Metal			
	Rp0.2 MPa	Rt0.5 MPa	Rm MPa	Y/T or Rp0.2/Rm		Rp0.2 MPa	Rt0.5 MPa	Rm MPa	Y/T or Rp0.2/Rm
Average values	612	612	664	0.92		658	657	741	0.89
Minimum values	599	598	657	0.91		649	649	728	0.88
Maximum values	623	623	671	0.93		668	668	754	0.90

By comparing the all-weld metal tensile properties with those of the parent material, the weld metal strength mismatch level can be quantified. The analysis in Table XI is based on the yield strength (Rp0.2), the flow stress (average of yield and ultimate tensile stress) and the ultimate tensile strength (Rm). The overmatch level obtained was close to the targeted value.

Table XI. Level of Weld Metal Strength Overmatch (%)

	Rp0.2	Flow Stress	Rm
Average values	7.5	9.6	11.5
Minimum values	4.2	6.4	8.5
Maximum values	9.2	11.5	13.6

After notching the wide plates were manually welded at their extremities to heavy loading lugs, having a curvature matching the pipe curvature. The assembly was then mounted horizontally in an 8000 kN testing machine, see Figure 18. The tests were carried out at -20 ºC; this temperature was achieved and maintained for at least one hour before loading was started by circulating refrigerated methanol, through specially designed cooling boxes having the same curvature as the pipe and firmly clamped against the outer walls at either side of the weld.

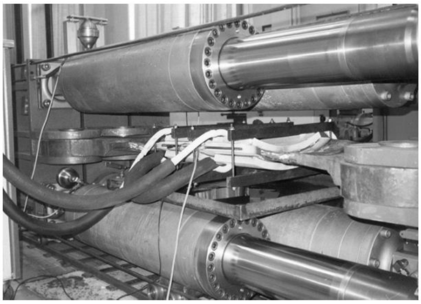


Figure 18. Wide plate specimen with cooling boxes in the 8000 kN tensile testing rig.

The wide plate specimens were strained to failure under displacement control with the load being applied transverse to the weld and the notch (equi-stress type of wide plate test). During testing, the applied load, the overall elongation (measured on a gauge length of 750 mm straddling the weld and the notch at mid-span), the pipe metal elongations (gauge lengths 200 mm), and the Crack Mouth Opening Displacement (CMOD), measured at the root side on a gauge length of 8.0 mm straddling the notch at mid-length, were measured, as detailed in Figure 17.

Table XII contains the values of the gross section stress, gross (overall) strain, CMOD, the remote pipe metal strain and the failure condition at the maximum load recorded during the wide plate tests. The specimen with the notch at the weld metal centreline failed at a remote strain of 4.1% while the HAZ-notched specimens survived remote strains of 3.3% and 1.2% respectively, the measured CMOD values being in line with these observations. All three curved wide plate tests exhibited GSY behaviour. (GSY – Gross Section Yielding)

During the weld metal centreline test a maximum load instability was obtained and the specimen finally failed by unstable pop-through. One of the specimens with a notch in the heat affected zone also failed by maximum load instability followed by unstable fracture whilst the other failed by unstable fracture initiation.

Table XII. Summary of CWP Test Results at Maximum Load

Notch position	Gross failure stress, MPa	Overall failure strain, %	CMOD mm	Pipe metal failure strain, %	Wide plate performance
WMC	688	4.6	3.89	4.1	GSY
HAZ / FL	670	3.6	2.24	3.3	GSY
HAZ / FL	645	1.4	1.50	1.2	GSY

The difference between the results for the two HAZ specimens was attributed to the presence of weld porosity at the artificial crack tip, indicated by the white arrow in Figure 19, which has been attributed to repair actions undertaken during the welding of the girth weld. The grey arrow indicates the zones of insignificant pop-in adjacent to the artificial defects and the black arrow points to a region of stable crack extension.

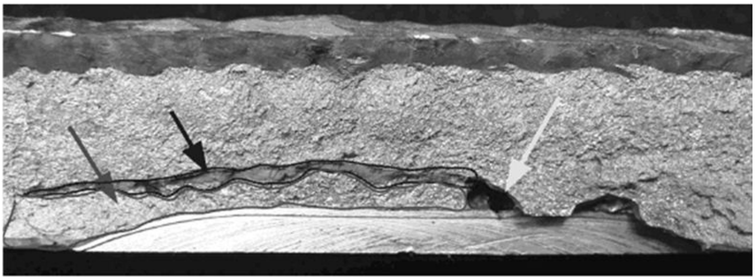


Figure 19. Fracture face of the second specimen with the notch in HAZ. (Arrow identification given in text).

However in all three cases, the remote applied (gross) failure stress exceeded the pipe metal yield stress and the pipe metal strains measured at failure were all in excess of 0.5%. These observations indicate that gross section yielding (GSY) was reached in all three specimens and this performance can be attributed to the beneficial effect of weld metal strength overmatching which effectively shields defects from the applied deformation. Despite the pop-in arising from the presence of weld porosity, it was shown that the girth weld had adequate flaw tolerance, with respect to fracture initiation, for low temperature application. It was concluded that the FCAW girth weld in the high Nb alloyed X80 pipe can, at a temperature of -20 °C, tolerate at least 3.3% strain with a 3 x 50 mm circumferential surface breaking defect present in the weld root of a sound weld. In the presence of weld porosity the strain limit was reduced to 1.2%.

Overall Conclusions

The results presented here show that very good impact toughness can be obtained on the fusion line and in the HAZ for the higher-niobium low-carbon compositions studied as industrial heats, at least comparable to or superior to other types of pipeline and structural steels. For the range of laboratory compositions studied there was no statistically significant detrimental effects of niobium on the 27 J or 50% upper shelf energy transition temperatures of simulated coarse-grained HAZs. This result is valid for 0.05 - 0.12% Nb and 0.02 - 0.07% C. The low carbon content of the steels was however beneficial to HAZ toughness as decreasing carbon from 0.09 to 0.04% reduced the 50% upper shelf energy transition temperature for the coarse-grained HAZ by about 25 °C for t8/5 = 30 s.

The HIPERC project also showed that, in addition to UOE pipe, the low-carbon higher-niobium concept can be used to make spiral welded pipe in strength classes X65 - X80. It has been shown that the pipes have good combinations of strength and toughness as measured using Charpy V and drop weight tear testing [5]. The girth weldability of the pipes was good and the pipe samples performed well in wide-plate tests, even in the presence of weld porosity.

It was also demonstrated that a low-carbon, higher-niobium chemistry allows the full-scale production of S420ML in 50 mm thickness and S460ML in 20 mm thickness plate using lower levels of controlled rolling and with air-cooling. The results presented in the HIPERC [1] project suggest that the Euronorms EN 10025-4 and EN 10208-2 could be changed to permit the use of higher levels of niobium, up to 0.12%, when using significantly lower carbon contents. In the author's opinion this upper limit for niobium could probably be reasonably extended for specification purposes to 0.15%. Furthermore, in the case of low carbon contents, it is recommended that higher levels of manganese are allowed in the structural steel standard EN 10025-4.

References

1. L. Drewett et al., "HIPERC: A Novel, High Performance, Economic Steel Concept for Linepipe and General Structural Use" (Research Fund for Coal and Steel Contract Number RFSR-CT-2005-00027, Final Report, 2009, EUR 24209 EN).

2. M. Pérez-Bahillo, B. López and A. Martín-Meizoso, "Effect of Rolling Schedule in Grain Size of Steels With High Niobium Content," *Proceedings of 10th Spanish National Congress on Materials 2008,* San Sebastian, Spain (18-20 June, 2008).

3. M. Pérez-Bahillo, "Study of Low Carbon Microalloyed Steels with High Niobium Contents, a Statistical Approach" (Ph.D. thesis, Universidad de Navarra, 2009).

4. J. Brózda and M. Zeman, *Weldability of Micro-alloyed Steel with Higher Niobium Content* (Biuletyn Instytutu Spawalnictwa W Gliwicach, Nr. 5/2008, Rocznik 52, ISSN 0867-853X).

5. B.Ouaiss et al., "Investigations on Microstucture, Mechanical Properties and Weldability of a Low Carbon Steel for High Strength Helical Linepipe" (Paper presented at the 17th Biennial Joint Technical Meeting on Pipeline Research, Milan, 11-15 May 2009).

6. S. Webster and L. Drewett, *The EU Project HIPERC, Niobium Bearing Structural Steels* (The Minerals, Metals & Materials Society, 2010), 201-218.

7. S. Webster and L. Drewett, "The HIPERC Project: The Use of Nb for High Performance and Economy for Linepipe and General Structural Use," *Proceedings of 6th International Conference on High Strength Low Alloy Steels 2011*, Beijing, China, (2011).

8. R. M. Denys et al., "An Engineering Approach to the Prediction of the Tolerable Defect Size for Strain Based Design," *Proceedings of the Fourth International Conference on Pipeline Technology 2004*, Oostende, Belgium, 1, (2004), 163-182.

9. A Di Schino, M. Guagnelli and G. Melis, "Seam Weld Assessment for CBMM," private communication.

Acknowledgements

The author is deeply indebted to all of the project participants: L. Drewett, S. Bremer, M. Liebeherr, W. de Waele, A. Martin-Meisozo, J. Brózda , M. Zeman, B. Zeislmair, H. Mohrbacher, D. Porter and N. Gubeljak for the use of some of their results in this paper but also for their contribution to the success of the project.

The HIPERC project was financially supported by the ERFCS.