Niobium Bearing Structural Steels
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THE EU PROJECT HIPERC - HIGH-PERFORMANCE, ECONOMIC STEEL CONCEPT FOR LINEPIPE AND GENERAL STRUCTURAL USE

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Abstract

This paper discusses the key highlights of a current EU collaborative steel research project involving 10 partners which has examined the fundamental principles of higher niobium steels in order to develop process-routes/compositional combinations that establish the suitability and limitations of this steel type for different market sectors.

The approach taken has been to determine the composition-microstructure-mechanical property relationships for this steel type for a range of processing conditions. The conditions simulated the hot processing of flat and coiled-plate products, their processing to pipe and weldability both during pipe production and in the field. Running in parallel with the simulation in the laboratory, trials via commercial production routes of the four steel-making partners have been undertaken. The results of the plate, pipe and welding products have been characterized and compared with the laboratory findings. Subsequently, all of the results have been used to develop models to relate composition, microstructure, and mechanical properties with the processing condition.

Introduction

The overall aims of the work being undertaken with the HIPERC project are to:

- Develop the metallurgical concept and understanding of the use of high niobium levels for use across a range of products and to determine the limits of what can be achieved;
- Establish the limits, in terms of relevant properties and chemical composition/metallurgical constituents, that conventional rolling mills can achieve using this new steel type for both thick wall pipeline and constructional grade steels;
- Understand the steel's weldability and weld properties for a range of welding processes, and;
- Understand both the economic and technical factors which govern the manufacture and use of this steel type across several market sectors.

The technical work has been divided into five main work-packages each covering a different aspect of the work or product area. The major aspects of the project are summarised in this paper and some of the results available to date highlighted.

Background

The concept of a pearlite-free steel with a low carbon content (<0.02%) based on using niobium levels of up to 0.11% was first described some thirty seven years ago [1] and a steel based on 0.04%C, 1.60%Mn, 0.25%Mo and 0.06 to 0.08%Nb was produced by IPSCO and successfully applied by the TransCanada PipeLine Company Ltd. for a major expansion project in 1971/72 [2]. Based on this first use of the 'acicular ferrite', i.e. low-carbon bainite, concept several steel companies in North America, Europe (Italy, France) and Japan conducted research work and carried out industrial production. However, the low carbon bainite alloy design declined in importance as a result of the molybdenum shortage at the end of the 1970s. Therefore the polygonal ferrite, pearlite containing, niobium plus vanadium microalloyed steel became the most relevant grade for line pipes. Following the results of some demonstration heats [3] a decade later the interest in the concept of low carbon bainitic pipe steel was reintroduced for selected applications, particularly since the possibility of using a high temperature thermomechanical rolling route to provide a bainitic microstructure without molybdenum additions was a strong economic attraction. The chemical composition proposed was based around 0.03% carbon, 0.10% niobium, titanium (0.014%) to fix the low nitrogen content (0.0035%) and calcium treatment of low sulphur (0.0008%) steel.

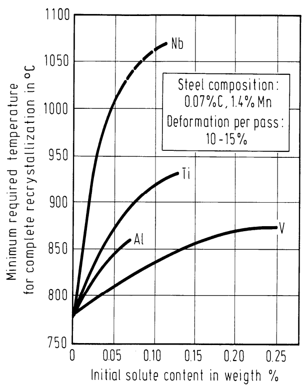


Figure 1. Retardation of recrystallisation by microalloying elements [4].

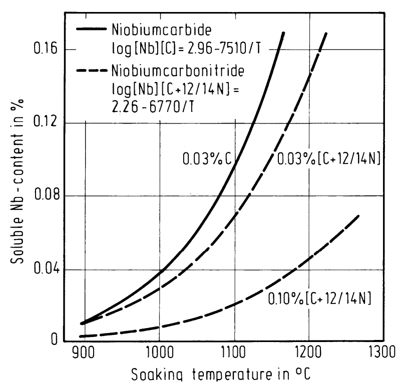


Figure 2. Solubility of niobium carbide and carbonitride [5,6].

Thermomechanical rolling is used to maximise grain refinement and thus achieve both higher strength and toughness. It is the standard means to produce plate for high strength large diameter line pipe and in recent years has also become the preferred route for producing higher strength, weldable steels for the construction and transport industries. It is characterised by processing austenite in the temperature region of non-recrystallisation, which results in an enhanced number of nucleation sites for the austenite to ferrite transformation. When the amount of solute niobium is increased, retardation of austenite recrystallisation is observed at significantly higher temperatures, Figure 1 [4], thereby allowing the benefits of thermomechanical rolling to be achieved at higher temperatures and hence lower rolling loads. Low carbon contents and the fixing of nitrogen with titanium, an element with higher affinity for nitrogen than niobium, prevents niobium carbonitride formation and allows the higher niobium content to be easily dissolved during reheating of the slabs, Figure 2 [5,6].

Steels based on the above concept have been investigated for use as X70 and X80 linepipe steel grades, using a wall thickness up to about 20mm, by several steel companies in a trial organised by CBMM. The results obtained were very promising, prompting a wider interest in the steel concept and led directly to the establishment of this project. The accepted opinion at the start of the project was that the steel had a good combination of strength and toughness up to about 20mm thickness and that acceptable strength levels could be achieved by both air and accelerated cooling, see Figures 3 and 4.

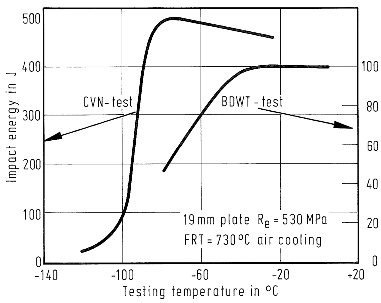


Figure 3. Toughness results for a low-carbon bainitic steel.

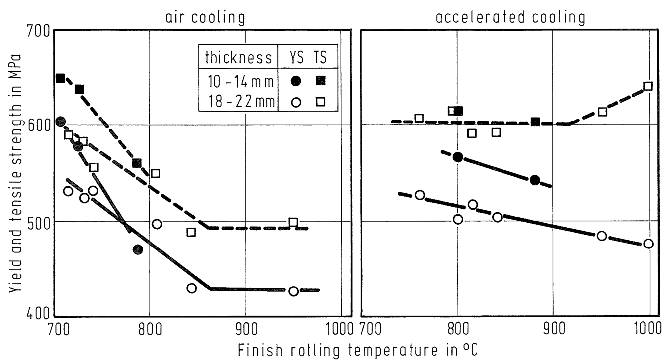


Figure 4. Tensile properties as a function of rolling conditions (1.50 % Mn, high Nb steel).

Given this evidence it was considered that potential existed to utilise the metallurgical concept for general structural plate use and for thinner, coiled-plate for both pipe production and general use. However several questions and uncertainties exist. For example a generic problem, for pipe, and certainly for general plate use, is that specifications limit the use of Nb to less than 0.06% or even lower. It is believed that this limit was introduced because of the negative influence of Nb on the heat affected zone (HAZ) toughness of pipe with a carbon content of about 0.12%. This, together with the poor austenite processing conditions in the days before controlled rolling, produced low toughness Widmanstätten microstructures [7], which made it prudent to limit the niobium content. However, modern steels utilise carbon levels typically below 0.08%, in order to avoid the peritectic reaction during solidification, which can be responsible for surface cracks in continuously cast slabs and for enhanced segregation. In such steels no negative effect of niobium is known and the information available suggests an excellent level of HAZ toughness.

There is also conflicting evidence regarding the limits for pipe plate processing regarding the strength and toughness levels which can be achieved for a given process route. And, importantly, there did not seem to have been a structured look at the steel composition limits which are possible to achieve the metallurgical conditions required.

The above aims and observations dictated the content of the project undertaken.

Project Structure

The project has been coordinated by the Research and Development organisation of Corus UK Ltd and the other steel organisations involved are: Salzgitter Mannesmann Forschung GmbH, Germany; Ruukki, Finland and ArcelorMittal OCAS, Belgium. The other industrial company was CBMM (Europe), The Netherlands, whilst the universities are: Ghent University, Belgium, University of Maribor, Slovenia and Rheinisch Westfälische Technische Hochschule Aachen (RWTH), Germany. The research organizations are: Instytut Spawalnictwa, Poland and Centro de estudios e investigaciones tecnicas de Gipuzkoa (CEIT), Spain.

Several of these organisations led work packages as detailed below:

WP1 - Development of the Metallurgical and Processing Models
The WP is led by RWTH Aachen and the objectives of this task are:

- To define the range of compositions and processing conditions needed to simulate the alternative hot rolling and cooling routes available for the range of products concerned.
- To produce laboratory scale samples cast and processed under the defined range of conditions.
- To define and perform the microstructural, mechanical and weldability characterisation of the laboratory samples.
- To provide a basis for the optimisation of composition and processing for the range of products concerned.

WP2 - Thick-walled Pipe
The WP is led by Corus and the objectives are:

- To produce air-cooled plate with thickness in the range 15-25mm and to characterise the mechanical and microstructural properties of these plates.
- To produce welded pipe from the plates and identify any limitations associated with the new steel.
- To characterise the weldability and pipe properties.

WP3 - Hot-coiled Plate for Pipe
The WP leader is Sandrine Bremer from Salzgitter, SZMF and the objectives are:

- To produce hot-coiled plates on two commercial hot strip mills.
- To characterise the mechanical and microstructural properties of this hot-coiled plate.
- To produce spiral and high-frequency welded pipe from the hot-coiled plate.
- To characterise the strength and toughness of the pipes and their seam welds.
- To characterise the weldability of the pipes for both seam and girth welding.

The overall aim of this work package is to determine the composition and hot rolling parameters that allow the economic production of high toughness pipes in the strength classes X70 and X80 or higher.

WP4 - Plate for General Construction
The WP leader is Martin Liebeherr from OCAS, with the following objectives:

- To produce plate with thickness up to 50mm and to characterise the mechanical and microstructural properties of these plates.
- To characterise the weldability of the high niobium steel using SAW, MIG, MMA and laser welding and cutting techniques.

WP5 - Industrial Implementation
The WP leader is David Porter from Ruukki and the objectives are:

- To analyse the technical and economic benefits of the new steels in the three product sectors studied.
- To identify and justify changes to the relevant Euronorms to enable the widespread application of the new steels.

Experimental Design of Laboratory Casts

The overall purpose of the fundamental studies undertaken has been to characterise and quantify the influence of a range of alloying elements upon the mechanical properties which can be obtained over a wide range of processing conditions using the ‘high niobium’ steel concept. A series of three experimental designs using a total of 24 laboratory casts have been used so that the influence of nine alloying elements; C, Mn, Nb, Cr, Mo, Ni, Cu, Ti and B can be assessed. The design of the steel composition matrix used was based on a statistical approach using an intelligent design of experiments (DOE) with a three-stage approach. The first stage was a half fractional factorial design with variations of Mn, Cr, Mo, Ni and Cu at two levels to determine the effects of these elements with respect to bainite formation and mechanical properties (strength and toughness). The second stage was a full factorial design dedicated to identifying the border conditions of the high temperature processing (HTP) concept and varies C and Nb at two levels different to those in stage 1. The third stage, which is also a full factorial design, investigates the influence of B by adding B and Ti at two levels. Since only B in solid solution is effective for the phase transformation, the formation of BN was avoided using Ti additions. The levels of Ti in stage 3 refer to Ti:N above and below the stoichiometric ratio assuming a N content of 40ppm. Table 1 summarises the design of the compositions and its three stages.

The experimental ingots were made and processed by OCAS and were each of 80kg, produced in a vacuum furnace. Nine blocks were cut from each ingot and 12mm thick plates were rolled from each block using two different reduction ratios (RR) below an assumed no recrystallisation temperature, Tnr, of 1,050°C, followed by three different cooling strategies, to provide six different processing conditions for each steel chemistry. The cooling conditions were selected to simulate air-cooling of thick plate, accelerated cooling, at 10°C/s, of thick plate or coil-plate, and processing of coil-plate with coiling at 550°C by accelerated cooling at 10°C/s down to 550°C, followed by slow cooling at 30°C/h. Two more blocks were rolled in order to supply one plate for dilatometer and torsion testing and one for welding simulations and one block was a spare in case of problems during processing.

Table 1. Design of cast chemistries in the laboratory model.

Stage 1

Level	C	Nb	Ti	B	Mn	Ni	Cu	Mo	Cr
Low					1.5	0	0	0	0
Base	0.04	0.10	0.015	0					
High					2.1	0.5	0.5	0.3	0.5

Stage 2

Level	C	Nb	Ti	B	Mn	Ni	Cu	Mo	Cr
Low	0.01	0.04							
			0.015	0	1.8	0.25	0.25	0.15	0.25
High	0.07	0.07							

Stage 3

Level	C	Nb	Ti	B	Mn	Ni	Cu	Mo	Cr
Low			0.008	0.000					
Base	0.04	0.10			1.8	0.25	0.25	0.15	0.25
High			0.025	0.002					

In order to give similar amounts of reduction in each pass during roughing of the laboratory plates, two thicknesses of starting block size were used for the reduction ratios of 2 and 4. In the case of RR = 2, three roughing passes and four finishing passes were applied while in the case of RR = 4, two roughing passes and five finishing passes were used. Table 2 summarises the rolling schedules.

Table 2. Rolling schedules and aim rolling temperatures.

RR at T<Tnr		**Start**	**R1**	**R2**	**R3**	**Total in roughing**	**F1**	**F2**	**F3**	**F3/F4**	**F4/F5**
2	Reduction (%)		22	22	22	52	16	16		16	16
	Thickness (mm)	50	39.1	30.7	24		20.2	17		14.3	12
4	Reduction (%)		23	23		40	24	24	24	24	24
	Thickness (mm)	80	62	48			36.4	27.6	20.9	15.8	12
Temp. (°C)		1200	1150	1100	1050		950	910	890	870	850

The reheating temperature was fixed to 1,200°C for all but one cast as, according to thermodynamic calculations, this temperature was sufficient to take the Nb into solution. In the case of the cast with a combination of 0.07%C and 0.07%Nb, a reheating temperature of 1,250°C was used. After reheating, a thermocouple was introduced into a pre-drilled hole in the blocks to allow the temperature in the centre of the blocks to be monitored during processing. The simulation of slow air-cooling relevant to thick plates required a cooling rate of 0.5°C/s and this was achieved by covering the plate with two slices of refractory wool. Accelerated cooling, with an aim rate of 10°C/s, was obtained using a horizontal cooling table equipped with a sledge for passing the steel plate through a 4m long array of water nozzles on both the bottom and topside. The water supply was stopped when the temperature measured by the thermocouple reached a pre-defined stop cooling temperature. Due to a certain reaction time of the installation and to slight variations in the position of the thermocouple with respect to the steel surface, the stop cooling temperature varied slightly from plate to plate. In order to be able to obtain a very narrow range it was decided to use an aim temperature of 600°C and this resulted in a range between about 580 and 600°C.

Obviously there was a degree of experimental scatter in the actual chemical compositions achieved and some casts had to be repeated but essentially the overall requirements of the experimental design have been met. All of the compositions are being assessed by determining the continuous cooling transformation (CCT) behaviour with deformation and the temperature of no recrystallisation. The mechanical properties of the 144 plates are being evaluated by tensile testing and the determination of impact transition curves and all of the microstructures are being extensively characterised. From these measurements, models of the effect of composition and cooling rate on structure and properties are to be constructed using regression techniques to identify the significant factors. The properties and microstructures of steels processed under commercial scale conditions will then be used to validate these models.

This work is still in progress and is due to be presented to the ERFCS Technical Committee, TGS6, in May 2009. Hence no definitive conclusions can be given at present but some examples of the work being carried out are given in the following sections.

Commercial Scale Casts

Commercial scale production and rolling has been undertaken by Corus, Ruukki and Salzgitter to enable experience of the processing of this steel type to be gained and to allow the observed properties and microstructures to be used to validate the laboratory model. Seven casts have been processed: one was used to produce 14.6mm, 20.9mm and 25.4mm thick plate and pipe and three have been processed as hot-coiled plate for pipe. Material has also been rolled to 20 and 50mm thick plate using normalised-rolling schedules used for structural plate. The analyses of the casts are given in Table 3.

Table 3. Compositions of commercial scale casts.

Cast ID	C	Si	Mn	P	S	Al	Nb	V	Cu
81913	0.053	0.18	1.59	0.013	0.0038	0.037	0.097	0.001	0.23
81351	0.043	0.20	1.96	0.007	0.0009	0.026	0.104	0.008	0.21
17721	0.033	0.22	1.82	0.005	0.0015	0.027	0.052	0.004	0.02
30257	0.040	0.20	1.49	0.012	0.0040	0.031	0.068	0.005	0.49
16685	0.047	0.32	1.73	0.009	0.0012	0.028	0.098	0.009	0.04
51569	0.07	0.45	1.69	0.013	0.002	0.04	0.05	0.006	0.21
02098	0.079	0.38	1.66	0.012	0.0026	0.032	0.044	0.079	0.06
	Cr	**Ni**	**N**	**Mo**	**Ti**	**Ca**	**B**	**Pcm**	**CEV**
81913	0.26	0.17	0.0059	0.002	0.016	0.0013	-	0.17	0.40
81351	1.01	0.22	0.0075	0.000	0.014	0.0018	0.0003	0.21	0.60
17721	0.21	0.05	0.0070	0.003	0.013	0.0026	0.0003	0.16	0.38
30257	0.04	0.41	0.0046	0.008	0.014	0.0013	0.0019	0.16	0.35

16685	0.27	0.04	0.0082	0.069	0.018	0.0012	0.0001	0.17	0.42
51569	0.05	0.31		0.005	0.017	0.0017	0.0023		
02098	0.04	0.06	0.0050	0.004	0.003	0.0020	-		

Corus processed cast 81913 to 14.6, 20.9 and 25.4mm thick plates, from an initial slab thickness of 230mm, using conventional rolling practices for pipe processing studies and to 20mm and 50mm thickness plates for examination of the potential for general structural steel. Ruukki has made production trials using two heats 81351 and 17721. These have been cast into 210mm thick slabs, hot-rolled into strip with a thickness of 10, 12 and 16mm and processed into spiral-welded pipes with diameters of 813 and 1,220mm. In addition, one 250 mm thick slab from Salzgitter has been rolled to a 10mm thick strip and made into spiral-welded pipe with a diameter of 610mm. Cast 81351 was made using a low-carbon high-niobium approach with high levels of manganese and chromium together with some copper and nickel in order to discover the highest strength obtainable without the use of molybdenum or boron. Molybdenum was omitted due its high cost, whereas boron was omitted in the belief that this would enable better drop weight tear test (DWTT) transition temperatures to be obtained. Cast 17721 contained lower levels of all alloying elements than in cast 81351 with no additions of copper or nickel at all. The niobium content was halved and the level of chromium reduced from 1.0 to 0.2%.

Salzgitter has produced one heat 30257 that was cast on a twin strand continuous caster into 250mm thick slabs. Four slabs have been rolled to strips of 14.1mm for large diameter pipes and one slab to 8mm, which may be applied for general structural use. The pipe diameter was 1,067mm with a strip width of 1,500 mm. The Salzgitter material was microalloyed with boron. In terms of Pcm and CEV, it was similar to cast 17721 with the lower manganese being compensated for by higher nickel and copper, niobium was somewhat higher too. The addition of boron was made to suppress P from the grain boundaries and enable an increase in coiling temperature to levels ~ 600°C without temper embrittlement.

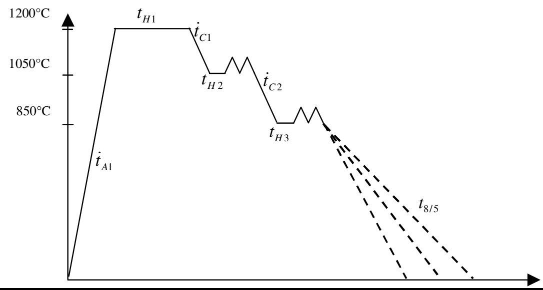
At Ruukki, hot rolling schedules were designed with different combinations of aim finish rolling temperatures (FRT) of 850 and 890°C and aim coiling temperatures (CT) of 500 and 550°C. Slab reheat temperatures were constant at 1,250 °C and it was intended that roughing finish temperatures (RFT) would be relatively high at about 1,100°C. Salzgitter used different coiling temperatures whereas the slab re-heating temperature was maintained at 1,220°C for the slabs used for pipe making. FRT values were also kept constant while coiling temperatures of 575, 600 and 650°C were targeted.

Material from some of the commercially produced casts has been processed through the laboratory to the six conditions and the mechanical properties of these and all of the commercially processed steels will be used to validate the models developed from the laboratory programme.

CCT Diagrams

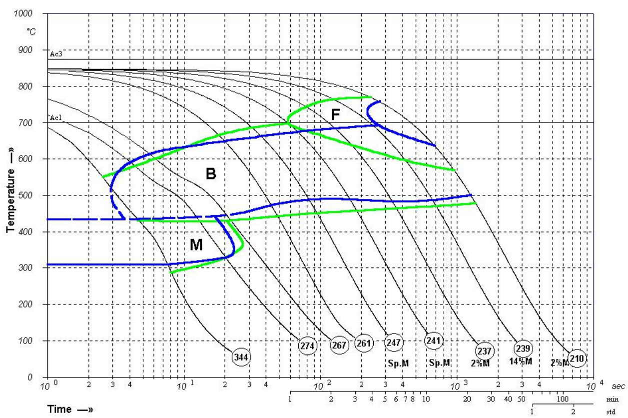
This work has been carried out by Aachen University and the conditions used for each cast to determine the CCT diagrams are shown in Figure 5. The heating and cooling rate up to the deformation steps is 5K/s, the samples are heated to 1,200°C and austenitised for 10 minutes. A holding time of 3s is applied before each of two deformation steps, where the rate of deformation is 3/s and the strain at both deformation steps is 0.6.

The first stage experimental design is such that the effect of a particular element is not readily shown, but in the second and third stage designs the effect of C, Nb, Ti and B may be readily seen. As examples, the effect of increasing Nb from 0.048 to 0.079wt% is shown in Figure 6 for an 0.08%C, 1.8%Mn, 0.25%Ni, 0.15%Mo, 0.25%Cu, 0.25%Cr steel, and the effect of increasing C from 0.02 to 0.08wt% in a 1.8%Mn, 0.25%Ni, 0.15%Mo, 0.25%Cu, 0.25%Cr, 0.08%Nb steel is shown in Figure 7. Niobium has enlarged the bainite field, as has carbon which has also decreased the transformation temperature.

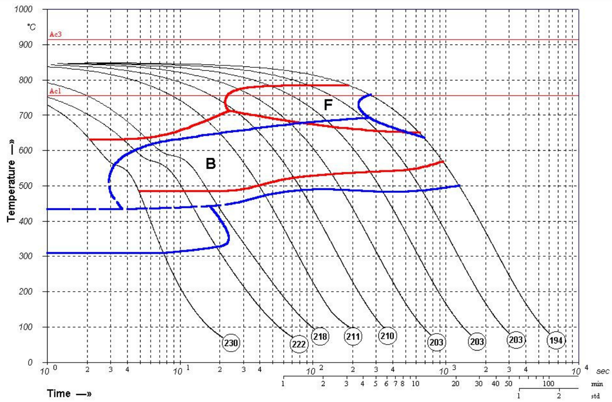


Time 800 – 500 °C	4	10	16	35	70	140	280	600	1200
Cooling rate, °C/s	75	30	18.75	8.57	4.29	2.14	1.07	0.50	0.25

Figure 5. Schedule of the reheating and deformation for the determination of CCT diagrams.



Green = 0.048 wt% Nb, Blue = 0.079 wt% Nb
Figure 6. The effect of increasing Nb from 0.048 to 0.079wt% in a 0.08%C, 1.8%Mn, 0.25%Ni, 0.15%Mo, 0.2%Cu, 0.25%Cr steel.



Red = 0.02 wt% C, Blue = 0.08 wt% C
Figure 7. The effect of increasing C from 0.02 to 0.08wt% in a 1.8%Mn, 0.25%Ni, 0.1%Mo, 0.25%Cu, 0.2%Cr, 0.08%Nb steel.

Temperature of Non-Recrystallisation

This work has been carried out by CEIT using a procedure developed by Jonas and co-workers [8] for determining the non-recrystallisation temperature, T_{nr}. This uses a Mean Flow Stress (MFS) vs. Inverse Absolute Temperature plot derived from multi-pass torsion tests. An induction furnace was used to heat the specimens to 1,250°C for 15 minutes to dissolve the Nb, the specimens were then cooled to 1,150ºC and at this temperature the first pass of deformation was applied. Deformations of $\varepsilon = 0.3$ with a strain rate $\dot{\varepsilon} = 1\ s^{-1}$ were applied at constant temperature steps of 20ºC down to 690ºC. This means that the number of passes was 24 with the interval between passes being 20 seconds and the cooling rate was 1ºC/s. The stress-strain curves obtained from 4 specimens used to study the influence of specimen size are shown in Figure 8. There was good reproducibility and the different thickness did not affect the stress-strain behaviour. The curves showed an increase in stress as the temperature dropped and there was a greater tendency towards hardening after approximately 10 passes. After 19 passes a reduction in the level of stress was observed, denoting the start of the $\gamma \rightarrow \alpha$ phase transformation.

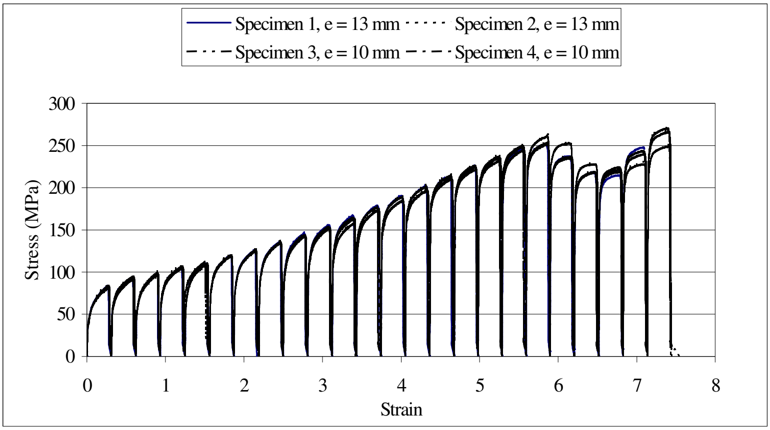


Figure 8. Multi-pass torsion test.

The Mean Flow Stress vs. Inverse Absolute Temperature plot determined from these four tests showed three different regions, see Figure 9.

- Region I: Where it is assumed that complete recrystallisation takes place between passes and that the increases in stress from pass to pass are only due to the drop in temperature.
- Region II: Where recrystallisation between passes is inhibited by strain induced precipitation. The stress increases more rapidly due to both the temperature drop and the accumulation of strain.
- Region III: Corresponds to the austenite-ferrite region. The stress reduction from the start of the transformation of austenite to softer ferrite phase (Ar_3 temperature).

The T_{nr} value is determined from the intersection between the regression lines of the points corresponding to regions I and II.

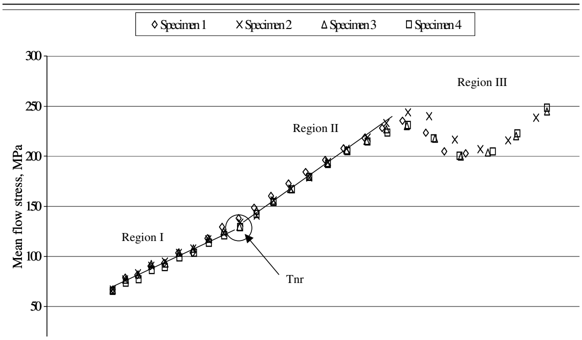


Figure 9. Mean flow stress, MFS, plotted against the inverse of the absolute temperature.

Microstructures

This work has also been carried out by CEIT. In order to evaluate structure – property relationships in this project it has been necessary to have a technique for determining a grain size for microstructures that may vary from ferrite - pearlite structures to bainitic structures. The approach taken has been to use electron back-scattered diffraction techniques to quantify the grain size. This approach allowed the grain sizes based on different angles of grain boundary misorientation to be assessed.

The work has looked at the characterisation of the microstructure in terms of the distribution of the number fraction of grains where bainite characteristically shows a larger number fraction of low angle boundaries compared with a ferrite pearlite microstructure [9]. An example of the analysis is illustrated in Figure 10.

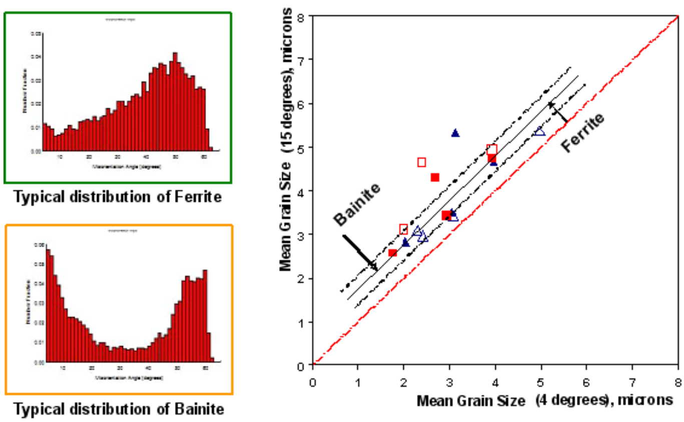


Figure 10. Number fraction / misorientation angle distributions for ferrite – pearlite and bainite.

Further characterisation of the accelerated cooled and simulated coiled microstructures has been undertaken through metallographic examination using four different etchants to identify martensite and austenite regions. The etchants used were: 1) 2% Nital for 10 seconds, 2) Le Pera reagent for 20 seconds, 3) 4% Picral for 30 seconds followed by 10% sodium metabisulphite for 7 seconds, and 4) 10% sodium metabisulphite for 5 seconds followed by Klemm's reagent for 60 seconds.

Mechanical Properties

The properties obtained in the experimental casts are shown as graphs of proof stress and tensile strength against impact transition temperature in Figures 11 and 12 respectively. Conditions C and D are for air-cooled plates with rolling reduction ratios (RR) of 2 and 4 respectively, E and F are for accelerated-cooled plates, with RR of 2 and 4 respectively, and G and H are the plates simulating the coiled condition, with RR of 2 and 4 respectively. The proof stress and tensile strengths covered by the laboratory rolled plate conditions range from

~ 450 to 770MPa and from ~ 520 to 910MPa respectively, while the impact transition temperatures range from ~ - 150 to + 25°C. The effects of the various elements are not yet confirmed. The effect of increasing RR from 2 to 4 was to lower the impact transition temperature and improve toughness.

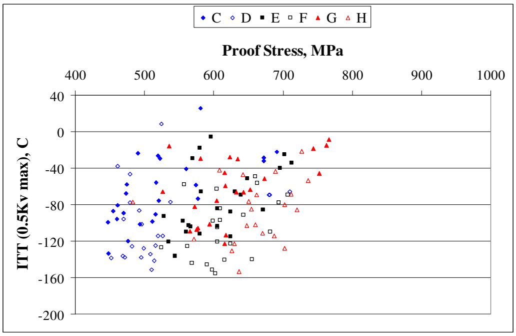


Figure 11. Proof stress v impact transition temperature.

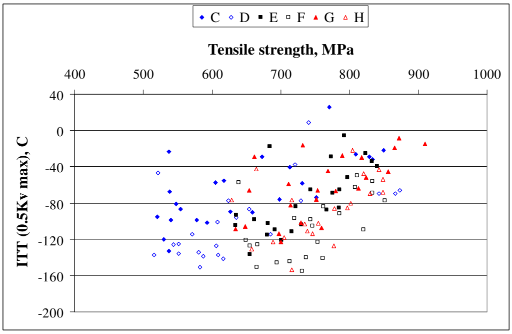


Figure 12. Tensile strength v impact transition temperature.

Weldability Studies

This work has been carried out by the Instytut Spawalnictwa, Poland with testing support from the University of Maribor and the University of Gent. The controlled thermal severity (CTS) test and Tekken test are common methods of examining resistance to hydrogen cracking in welds. Whilst the CTS test is sometimes used by pipe customers for linepipe pre-qualification purposes, it is known that the Tekken test provides results that are similar to the in-field girth welding of pipelines. Tekken tests to EN ISO 17642-2 have been carried out on some of the commercially produced steels to establish preheating requirements to avoid hydrogen cracking. Some CTS tests have also been carried out to confirm that HAZ hydrogen cracking is not an issue in the high Nb steel particularly when using no preheat and low hydrogen electrodes. The properties of the electrodes and welding wire used in the Tekken tests are shown in Table 4.

Table 4. Welding wire, electrodes and welding parameters used in the Tekken tests.

Brand	**Classification**	**Mechanical properties of weld metal (manufacturers data)**			**Diffusible hydrogen (ml/100g)**	
		$Rp_{0.2}$ (MPa)	**Rm (MPa)**	**Elongation (%)**	**Glycerine method**	**Mercury method**
SL 12G basic, very low H2	PN-EN 1599 E Mo B 32 H5	550	610	25	1.65	2.50
Pipeliner 8P+	PN-EN 499 E46 4 1Ni C 25	460 - 559	550 - 676	19 - 27	24.8	37.7

Steel	**Electrode**	**Specimen**	**Welding parameters**			**Heat Input**
			I (A)	**U (V)**	**V (cm/s)**	**E = U.I/v (kJ/cm)**
Plate PC943 from cast 81913	SL 12G	Tekken	144	23.5	0.34	9.9
	Pipeliner 8P+		118	24.5	0.34	8.5
	SL 12G	CTS	150	22.7	0.33	10.3
	Pipeliner 8P+		131	25.2	0.37	8.9
Strip 783078 from cast 30257	SL 12G	Tekken	148	22.5	0.33	10.1
	Pipeliner 8P+		118	24.6	0.34	8.5

Examination of the weld microstructures after welding identifies the conditions under which cracking occurs with the different consumables. Two commercial steel compositions have been assessed using plate PC943 from cast 81913 and strip 783078 from cast 30257. Four slices through each weld were examined and these examinations showed that cracking did not occur in the HAZ of the welds even with high levels of diffusible hydrogen. Cracking of the weld metal did occur with diffusible hydrogen levels of 37ml/100g found in Pipeliner 8P+ when no pre-heating was applied, see Figure 13.

Laboratory scale simulation of the weld HAZ has been carried out using a thermal cycle simulator to examine the effect of cooling rate. Samples were reheated to 1,250°C and cooled at controlled rates 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 at room temperature has been assessed for these two steels [10]. The results for the boron-containing commercial cast 30257; processed to 14mm thickness hot-coiled strip is shown in Figure 14.

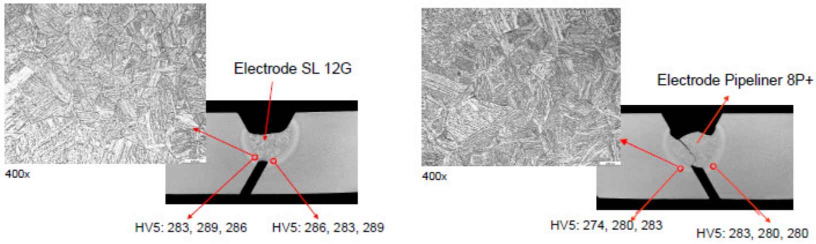


Figure. 13 Examples of the Tekken test examinations.

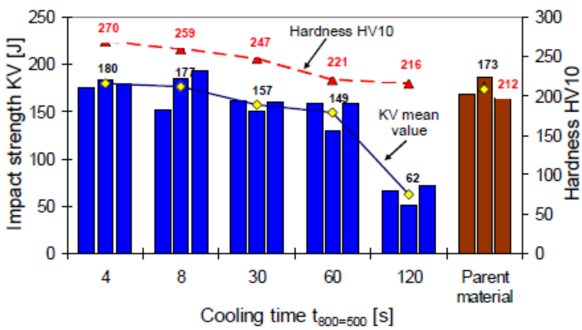


Figure 14. The effect of $t_{8/5}$ on impact toughness and hardness measured at room temperature.

Transition curves for the parent steel and for simulated weld conditions with $t_{8/5}$ of 8s and 30s have been determined and a comparison of these properties with the results from real welds is given in Figure 15. It can be seen the simulated results represent a lower bound.

Changes to standards

A major aim of the project is to provide sufficient information in order to allow changes to be made to the relevant standards and so enable the widespread application of 'low carbon high niobium' steels. The completion of the models based on the experimental results and, if successful, the ability of these models to predict the properties of other compositions through both laboratory and commercial-scale processes should enable this work to submit proposals to the various technical committees with justifications for increasing the limits on niobium.

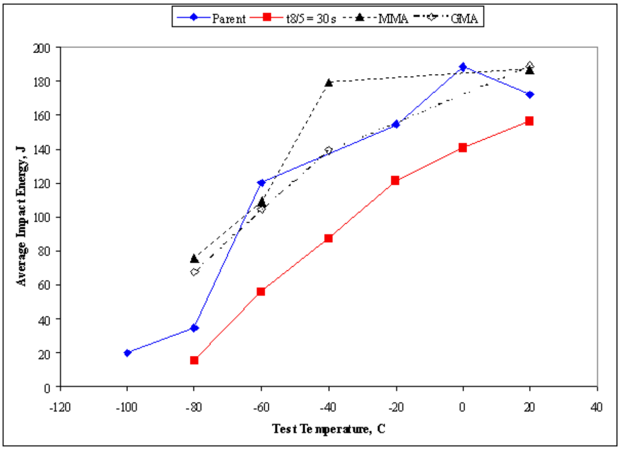


Figure 15. Comparison of parent material, simulated and real welds on coil-plate 783078

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