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DEVELOPMENT OF STANDARDS & SPECIFICATIONS FOR HIGH STRENGTH LINE PIPE

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Abstract

The needs of the international gas industry to transport bulk gas from remote gas fields to market have prompted the development of ultra-high strength line pipe which will be required for the economic construction of future long distance, high pressure gas pipelines. Until recently, the conventional limiting grade for such line pipe was API 5L Grade X80 or its ISO 3183 equivalent Grade L555.

Joint private development programmes between oil/gas companies and major steel pipe manufacturers have resulted in new higher strength pipes; principally grades X90 (625), X100 (L 690) and X120 (L830). The steel makers and pipe mills have designed alloy compositions and pipe processing routes to optimise mechanical properties in the line pipe, including high toughness for fracture control for arctic use. The oil and gas companies have conducted forming and girth welding trials on these new pipes together with extensive mechanical property evaluation and assessment of fracture arrest behaviour.

The industry is now ready to translate results of the long development programmes into national and international codes and standards for line pipe production and pipeline construction. This paper describes current work within API and ISO to standardise these ultra high strength grades of line pipe for industry use.

Introduction

The use of natural gas is set to grow dramatically on a world-wide scale. Nations who have signed up to the Kyoto Agreement are actively seeking to reduce their greenhouse gas emissions, so a switch from oil or coal to cleaner fuels such as natural gas is a step in the right direction and is influencing market demand.

Supplies from many of the present fields, although sufficient for immediate needs are inadequate for future markets, and even at present rates of usage, there is concern in Europe that the existing gas supplies will not meet all foreseeable demands in the event of an exceptionally cold winter.

More than ten years ago, recognition of this future scenario prompted several oil/gas companies to evaluate major gas fields around the world for development. Some potentially attractive gas fields are located in remote regions and are therefore distant from their ultimate markets. Such regions can also suffer from extreme climatic conditions which limit access to certain times of the year for infrastructure, construction and routine operations. Examples of some remote major gas fields include Algeria which supplies the markets of Western Europe, the Eastern Siberian fields which have potential markets in the Far East and the gas fields of Northern Alaska with potential markets in the lower 48 states of the USA.

The common factor with all of these gas fields is the need for very substantial investment in long distance, large diameter transmission pipelines to deliver the gas which inevitably constitutes a major cost element of such developments. Indeed, the ultimate cost of the pipeline may determine whether or not the project is economically viable.

Against this background, several oil and gas companies looked to the concept of higher strength line pipe which would not only reduce the amount of steel pipe to be purchased but which also has the potential to reduce other associated costs related to transportation and fabrication time at site. This is especially valid for girth welding time as high strength pipe allows a thinner pipe wall and/or the ability to operate the pipeline at higher pressures. Girth welding the pipeline is often the rate-determining factor for progress of the overall pipeline construction so a reduction of welding times by combination of advanced mechanised welding techniques and use of thinner wall of a higher strength line pipe, can result in substantial savings in terms of the logistics and personnel support costs for large construction teams operating in remote locations.

Around 10 years ago several oil/gas companies, in partnership with some of the world's leading steel and pipe mills embarked on programmes to develop higher strength grades of pipe initially with a target of producing pipe having a minimum yield strength of 690MPa (100 ksi) which became widely known as X100. Around the same time Exxon (now ExxonMobil), in association with two leading steel pipe-mills, unilaterally began development of an even higher strength linepipe, now known as X120 and having a specified minimum yield strength (SMYS) of 830 MPa (120 ksi).

During the last decade, prototype steels were developed, pre-production pipes were manufactured and extensively tested to evaluate material characteristics. The technology has been refined progressively to produce second and third generation ultra high strength steel pipes which have been used to demonstrate constructability, including field welding, pipe handling and cold bending technologies and to perform large scale tests to determine characteristics such as fracture control. These steels have probably undergone more intensive pre-production testing than many of the existing lower grades.

Standardisation and Specification

The industry is now ready to introduce these materials for standardisation and the grades L 625 (X90), L690 (X100) and L830 (X120) have been written into ISO Draft International Standard (DIS) 3183. It is intended that this ISO standard will ultimately be harmonised with a future edition of API 5L. The standard drafting is being handled by joint ISO and API working groups, namely ISO TC67/SC2-WG16 (Linepipe) and API WG 4183 (Linepipe) with detailed consideration of these higher strength materials being the subject of study directly by API WG 4193 (High Strength Pipes).

Standardisation involves obtaining consensus between interested parties who each table their own data in support of standardising their product. The individual manufacturers' X100 development programmes has led to several marginally different steel compositions; each manufacturer, favouring their own. Obtaining the necessary consensus in a standards working group invariably means that limits are widened to allow an "envelope" to be developed which embraces all but the most extreme limits. While this assists the standardisation process, it means that the user is generally obliged to write supplementary purchase specifications to customise the

pipe to the intended application and this generally implies specifying tighter limits or tolerances on composition and some mechanical properties.
At the lower end of the ultra high strength linepipe, an X90 grade has been included in DIS 3183 as it was developed almost by default early in the X100 programme and, since intermediate grades are allowed by API 5L, it is an ideal mid-point strength bridge between X80 and X100.

At the top end of this group of materials, the grade X120 is unique. It was developed and tested in comparative secrecy for almost a decade by Exxon in conjunction with selected steel mills and some technology was patented. Within the last 4 years, ExxonMobil published the first details of X120 which has widened interest in the alloy. Data supporting the inclusion of X120 has come to the API/ISO working groups exclusively from ExxonMobil and their collaborating steel makers.

In 2002 simultaneous applications were made for a new work item in API and ISO to include higher strength grades from X90 to X120 in API 5L and ISO 3183.

As a fundamental part of the proposed harmonisation of API 5L with ISO 3183, the working groups have agreed that the ultra-high strength linepipe grades should be standardised only as the higher product specification level PSL 2.

Summary of Development – Timescale

The first X100 pipeline was built in the 1960's by Columbia Gas in the USA. The linepipe used for that project probably bears little relationship to the more recently developed X100 pipes. The early X100 was briefly specified in API Standard 5LU which has since been discontinued. The present X100 steels have been developed since the early to mid 1990's primarily by five major steel companies who tuned their developments to the perceived needs of major oil and gas companies such as BP, Shell, British Gas and TransCanada Pipelines. The separate X120 programme between Exxon and selected steel-makers and pipe mills developed during the same period but few details were published until 2002.

Since that time, public attention has been drawn to both X100 and X120 encouraged by the initiative to standardise both grades along with X90. The joint working groups of ISO and API have included these grades in standards which were already the subject of revision and intended to be harmonised as a new ISO 3183 /API 5L Line Pipe Standard.

Applications of Ultra High Strength Linepipe

The principal area of application of the higher strength grades of line pipe is for long distance high pressure gas pipelines for natural gas. Regions such as Alaska and Siberia with large gas fields and which will require trunk pipelines more than 3000km long are obvious candidates for high strength line pipe but such materials may ultimately be exploited for shorter trunk pipelines operating at high pressure. The extremely cold temperatures of these regions impose challenges for any material and, in the case of the high strength steels, the need also for ductility and high fracture toughness at low temperature remains paramount along with the need to be able to resist running fracture or to quantify running fracture resistance in case a fracture should be initiated.

The development of X100 and X120 for gas pipelines has been exclusively in the product form of longitudinally submerged arc welded large diameter pipe, typically made from high quality plate by the UOE process. Such pipe is typically referred to as SAWL-UOE or simply UOE pipe. The developments have been typically in diameters from 30" to 52" and with wall thicknesses of 15 mm upwards. It is contended that production of X100 at wall thickness below 15 mm is not merited as lower grades of pipe such as X70 and X80 can meet market needs more economically.

As yet, there has been no parallel development of HFW (ERW) pipe although it has been reported in API/ISO working groups that the idea has been mooted by some pipe companies and it remains unclear if there is a viable market for smaller diameter high strength pipe with lower wall thickness at the present time.

One company has embarked on a noteworthy development programme to develop high strength seamless pipe, typically X100 grade but for sub-sea deepwater applications. At present, deepwater fields are being developed in the Gulf of Mexico and elsewhere in water depths of typically 2500 metres (6000 ft) which impose high external pressures on sea-bed flowlines and steel catenary risers. Weldable UHS seamless linepipe, made to stringent dimensional tolerances, would assist the design of collapse resistant flowlines with thinner walls. The same philosophy could apply to steel catenary risers (SCR's) although sections of these components are usually also subject to fatigue loading for which the higher strength material would offer little benefit.

Thus the principal envisaged use of X90, X100 or X120 is for the transmission of dry, generally lean composition, natural gas. In this role, such steels will be procured to a base standard which might be ISO 3183, a future edition of API 5L or the current CSA Z.245.1 but almost certainly supplemented in each case by a detailed procurement specification relating to the actual application. The latter is likely to be both technically and area specific.

At the present time, it is not envisaged that materials such as X90, X100 or X120 will be suitable for wet, fluid streams containing H_2S and CO_2 (sour service conditions) as typically, residual stress levels in welds could be high and hardness in weld zones exceed current guideline limits and extensive testing would be necessary to enable safe operating limits to be defined.

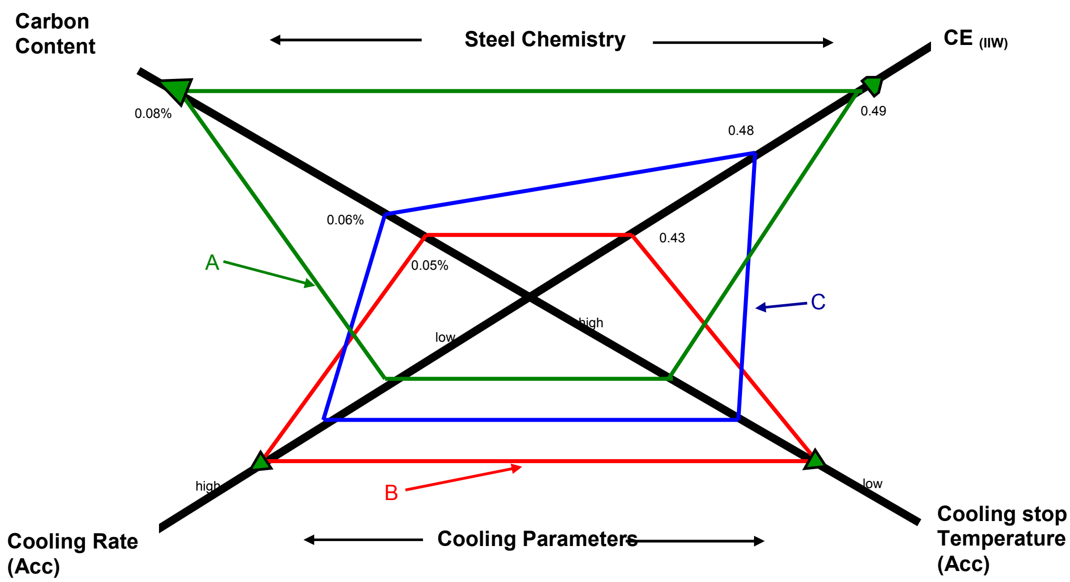
Composition of Ultra High Strength (UHS) Line Pipe

The UHS steel pipes made to date have been produced exclusively by some of the world's premier steel groups and pipe mills and have been the subject of extensive technical development. As far as is known, manufacture of steels for large diameter X100 and X120 pipes to date has been exclusively by the basic oxygen steel making process followed by ladle treatments and vacuum degassing resulting in low carbon steel with micro-alloy additions and exceptionally low sulphur and phosphorus content.[1]

Each manufacturer's prototype X100 was developed to their own preferred compositions, tailored to their own mill practices and subsequent plate rolling and pipe production. Much of the detailed information on X100 remains proprietary to each steel mill and, although this limits the amount of detailed data that is available to standardisation bodies, the situation for X100 is really little different from that which has always been the case for lower grades of pipe such as X65, X70 and X80.

The consequence of different manufacturers offering a range of typical compositions to the standards working group inevitably results in the standardized composition limits being an "envelope" into which all or most X100 will fit. Clearly then, a situation of *caveat emptor* prevails and the purchaser of UHS pipe must judge factors such as the composition required, the ability of the steel maker to achieve the specified general mechanical properties and particularly any project specific property requirements such as low temperature Charpy impact or CTOD values, crack arrest properties and weldability in the final pipe.

The achievement of a range of tightly specified mechanical and physical properties depends on chemical composition of the steel and subsequent processing through steel making and secondary refining, plate rolling using tightly controlled parameters and the process of pipe manufacture itself. However, the fundamental start of the process is composition and the effects of varying composition have been demonstrated simply by Hillenbrand and Kalwa [2] in a diagram presented at an earlier conference. Figure 1.



Acknowledgements.H-G Hillenbrand & C Kalwa; Europipe GmbH, Germany

Figure 1. Carbon Content and Processing for UHS Pipe Steel

The figure shows three approaches based on carbon content.

Approach "A" describes an alloy having a relatively high carbon content of typically 0.08 percent and a carbon equivalent value (CE) of 0.49. This is an easier composition for the steel maker to process as it allows X100 properties to develop in the plate at a low cooling rate and high accelerated cooling stop temperature. However, such a steel has the disadvantage of lower weldability and crack arrest toughness and such a steel is unlikely to achieve the required Charpy toughness at temperatures of typically minus 40ºC, as may be the case for an arctic gas transmission line.

Approach "B" utilises a steel of lower carbon (typically 0.05% max) and a CE of typically 0.43 percent. This would improve weldability but, to achieve the specified yield and tensile properties fast cooling rates and very low accelerated cooling stop temperatures would be required. This creates a challenge for the plate rolling mill whose finishing procedures must be very tightly controlled. Such a steel may form martensite, toughness control becomes more difficult and HAZ softening may occur after welding the longitudinal seam.

Approach "C" utilises a medium carbon content (typically 0.06%), resulting in a CE of 0.48 percent. This composition tends to optimise production flexibility, produces high levels of toughness and good field weldability.

Table I shows typical chemical compositions of four X100 pipes and seam welds.

Table I. X100 Pipe and Seam Weld Chemistry (Typical Examples) [4]

	C wt%	**Si** wt%	**Mn** wt%	**P** wt%	**S** wt%	**V** wt%	**Nb** wt%	**Ti** wt%	**Cr** wt%	**Ni** wt%	**Mo** wt%	**Cu** wt%	**Al** wt%	**B** ppm	$\mathbf{P_{CM}}$	$\mathbf{CE_{IIW}}$
Pipe A. Nominal 0.4Cr-0.5Ni-0.4Mo-0.5Cu-V-Nb-Ti (WT 19 mm)																
Pipe	0.027	0.20	2.00	0.006	<0.005	0.07	0.05	0.015	0.43	0.48	0.43	0.46	0.005	<5	0.223	0.609
Pipe Seam ID)	0.037	0.22	1.64	0.006	<0.005	0.05	0.03	0.010	0.56	1.10	0.58	0.33	0.013	<5	0.234	0.644
Pipe Seam OD	0.046	0.20	1.62	0.007	<0.005	0.04	0.03	0.010	0.50	1.09	0.51	0.31	0.012	<5	0.231	0.619
Pipe B Nominal 0.5Ni-0.25Mo-0.30Cu-Al-Nb-Ti (WT 14.9 mm)																
Pipe	0.066	0.10	1.91	0.008	<0.005	0.006	0.03	0.013	0.02	0.54	0.27	0.30	0.02	<5	0.209	0.500
Pipe Seam ID	0.068	0.13	1.88	0.009	<0.005	0.007	0.02	0.014	0.46	0.39	1.04	0.24	0.02	6	0.281	0.725
Pipe Seam OD	0.063	0.16	1.87	0.008	<0.005	0.007	0.019	0.016	0.34	1.75	0.6	0.26	0.017	7	0.265	0.698
Pipe C Nominal 0.5Ni-0.25Mo-0.3Cu-Al-Nb-Ti (WT 19 mm)																
Pipe	0.066	0.18	1.88	0.008	<0.005	0.005	0.05	0.018	0.022	0.49	0.26	0.30	0.04	<5	0.209	0.489
Pipe Seam ID	0.059	0.21	1.99	0.008	<0.005	0.007	0.04	0.02	0.36	1.00	0.78	0.26	0.026	6	0.269	0.704
Pipe Seam OD	0.053	0.2	1.91	0.007	<0.005	0.007	0.03	0.018	0.33	2.03	0.63	0.26	0.023	6	0.264	0.717
Pipe D Nominal 0.25Ni-0.3Mo-Al-Nb-Ti (WT 16.3 mm)																
Pipe	0.055	0.37	1.91	0.010	<0.005	0.005	0.05	0.02	0.03	0.24	0.28	0.01	0.023	<5	0.189	0.453
Pipe Seam ID	0.049	0.38	1.69	0.012	<0.005	0.006	0.03	0.03	0.04	0.17	0.34	0.01	0.023	30	0.190	0.420
Pipe Seam	0.05	0.38	1.64	0.012	<0.005	0.006	0.03	0.03	0.04	0.16	0.35	0.01	0.021	30	0.189	0.414

$$Pcm = C + Mn/20 + Mo/15 + Ni/60 + Cr/20 + V/10 + Cu/20 + Si/30 + 5B$$
$$CE_{IIW} = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$$

It should be noted that low carbon *per se* does not automatically result in a low carbon equivalent value as demonstrated by Pipe A where the high Mn, Cr, Ni, Mo and Cu alloy content has contributed to the overall CE_{IIW} of around 0.6 . It is generally accepted that the Pcm value is more appropriate than the IIW CE for all these low carbon ultra high strength alloys and for this reason, no limiting CE value has been specified in Table 5 of ISO DIS 3183, part of which has been reproduced in this paper as Table II. Here, the "envelope" of chemical composition limits for X90 (L 625), X100 (L 690) and X120 (L 830) are shown along with a limiting P_{cm} value of 0.25 for all three grades.

Table II. Chemical Composition for PSL 2 Welded Pipe [5]

Pipe designation	**Mass fraction, based upon heat and product analyses** % Maximum									**Carbon equivalent**[a] % Maximum	
	C[b]	Si	Mn[b]	P	S	V	Nb	Ti	Other	*CE*	P_{cm}
L245M or BM	0,22	0,45	1,20	0,025	0,015	0,05	0,05	0,04	e	0,43	0,25
L290M or X42M	0,22	0,45	1,30	0,025	0,015	0,05	0,05	0,04	e	0,43	0,25
L320M or X46M	0,22	0,45	1,30	0,025	0,015	0,05	0,05	0,04	e	0,43	0,25
L360M or X52M	0,22	0,45	1,40	0,025	0,015	d	d	d	e	0,43	0,25
L390M or X56M	0,22	0,45	1,40	0,025	0,015	d	d	d	e	0,43	0,25
L415M or X60M	0,12[f]	0,45[f]	1,60[f]	0,025	0,015	g	g	g	h	0,43	0,25
L450M or X65M	0,12[f]	0,45[f]	1,60[f]	0,025	0,015	g	g	g	h	0,43	0,25
L485M or X70M	0,12[f]	0,45[f]	1,70[f]	0,025	0,015	g	g	g	h	0,43	0,25
L555M or X80M	0,12[f]	0,45[f]	1,85[f]	0,025	0,015	g	g	g	i	0,43	0,25
L625M or X90M	0,10	0,55[f]	2,10[f]	0,020	0,010	g	g	g	i	—	0,25
L690M or X100M	0,10	0,55[f]	2,10[f]	0,020	0,010	g	g	g	i		0,25
L830M or X120M	0,10	0,55[f]	2,10[f]	0,020	0,010	g	g	g	i		0,25

a Based upon product analysis. For seamless pipe with t > 20,0 mm (0.787 in), the carbon equivalent limits shall be as agreed. The CE limits apply if C > 0,12 % and the Pcm limits apply if C ≤ 0,12 %.

b For each reduction of 0,01 percentage point below the specified maximum for carbon, an increase of 0,05 percentage point above the specified maximum for manganese is permissible, up to a maximum of 1,65 % for grades ≥ L290 or X42, but ≤ L360 or X52; up to a maximum of 1,75 % for grades > L360 or X52, but < L485 or X70; up to a maximum of 2,00 % for grades ≥ L485 or X70, but ≤ L555 or X80; and up to a maximum of 2,20 % for grades > L555 or X80.

c Unless otherwise agreed, the sum of the niobium and vanadium contents shall be ≤ 0,06 %.

d The sum of the niobium, vanadium, and titanium contents shall be ≤ 0,15 %.

e Unless otherwise agreed, 0,50 % maximum for copper, 0,30 % maximum for nickel, 0,30 % maximum for chromium, and 0,15 % maximum for molybdenum.

f Unless otherwise agreed.

g Unless otherwise agreed, the sum of the niobium, vanadium, and titanium contents shall be ≤ 0,15 %.

h Unless otherwise agreed, 0,50 % maximum for copper, 0,50 % maximum for nickel, 0,50 % maximum for chromium, and 0,50 % maximum for molybdenum.

i Unless otherwise agreed, 0,50 % maximum for copper, 1,00 % maximum for nickel, 0,50 % for chromium, and 0,50 % maximum for molybdenum.

j 0,004 0 % maximum for boron.

The wide compositional limits allowed by standards such as API 5L are used to manufacture and order lower grade pipes, e.g Grade B to typically X56 or X60 as stock material, held by distributors (stockists) but are generally unsuited for higher grade pipes without restrictions. However, the same standard is frequently used as a base on which supplementary purchase specification for the higher strength steels (e.g. X60 – X80) are written by users having project specific requirements. Much higher grade pipe (e.g. X65 – X80) is purchased this way and although such grades are regarded as "standard" by the steel maker, pipe-mill and petroleum/gas industry user, they are, in fact, "specials", based on existing grade designations but custom produced to suit the particular application. The ultra high strength grades may follow this pattern and individual purchase specifications e.g. Table III, although based on ISO 3183, API 5L or CSA Z245-1, will be used to fine tune chemical composition and other parameters or properties to custom design the pipe for the intended pipeline.

"The manufacturer shall nominate a preferred steel composition (heat and product analysis) within the following limits for each respective pipe grade for approval by the purchaser. The composition tolerances applied for each element shall also be subject to approval by the purchaser.

Table III. Typical Supplementary Specification for X90-X100 Steel Compositions.

Element [(a)]	**Wt %** [(b)]
Carbon	0.10% maximum
Manganese	0.80% - 2.00%
Silicon	0.05% - 0.35%
Sulphur	0.005% maximum
Phosphorus	0.015% maximum
Nitrogen	0.008% maximum
Vanadium	0.08% maximum
Niobium	0.05% maximum
Titanium	0.03% maximum
Aluminum	0.010-0.055%
Copper	0.50% maximum
Boron	0.0005% maximum
Calcium	0.006% maximum
Nickel plus Copper	1.00% maximum
Chromium plus Molybdenum	0.35% maximum
Vanadium plus Niobium	0.12% maximum
(a) No other element shall be added to the steel without the approval of the Purchaser	

Clearly, the advantage of this approach is that it can be used in enquiry to several manufacturers and the limits specified are sufficiently wide to embrace the individual manufacturing limits of more than one manufacturer, especially when UHS pipe may have to be sourced from more than one supplier. Thus the supplementary specification allows essential dialogue between the purchaser and manufacturer to begin.

A typical supplementary purchase specification can also be used to apply limits to Carbon Equivalent and/or Pcm; typical values being shown as below, Table IV

Table IV Limiting Carbon Equivalent and Pcm Values for X90 and X100

Parent Metal Grade	Carbon Equivalent (CE)	Pcm
X90	0.48 max	0.22 max
X100	0.51 max	0.22 max

By this means, the purchaser is in a position to negotiate a limit on the CE or Pcm that is more suited to the actual application, than may be permitted if bought to an API or ISO standard alone.

The pipe manufacturer must generally use more highly alloyed submerged arc welding wires for the internal and external seam welds of UOE pipe as shown in Table III. This is required to ensure that the specified hoop stress values can be met in the seam weld as well as in the parent pipe. The same principle would apply if X100 is produced as helical (spiral) welded pipe. This again forms part of the proprietary technology and intellectual property of the pipe mill and, in common with the lower grades of pipe, is not specified in the base standards. As for some of the conventional high strength grades, the composition of the seam weld is not specified in the base standards and must be the subject of dialogue between the supplier and client. A consequence of this is that, at the interface between the seam weld and the field girth weld, some local hardening may arise in the HAZ. Conversely, in the wide HAZ associated with the SAW seam weld, a small level of local HAZ softening has been noted in some lean composition X100 pipes. Factors such as these are not covered by the established standards and require the attention of the purchaser.

Manufacture of Ultra High Strength Linepipe

The processing route from the continuously cast slab to the mother plate for pipe manufacture is another area where the technology is proprietary to the manufacturer and therefore does not feature in standardization other than by specifying if the grade may be manufactured by thermo-mechanical controlled processing (TMCP) or by a quench and tempering route.

In the ISO format, pipes made from plate produced according to these conditions is usually designated “M”. At present the three ultra high strength grades X90, X100 and X120 in the DIS 3183 are designated M as the plate for most pipes to date has been produced by the TMCP process. Theoretically, the rolling of a low carbon microalloy plate followed by a quenching and tempering process is feasible for X100 but apart from some experimental or pre-production plates/pipes has not been used. The additional step of a tempering process makes the process economically unattractive to steel makers who already have accelerated cooling processes installed in their rolling mills and are able to produce the plate by the TMCP process. If the ultra high strength pipes are ultimately produced from quenched and tempered plate, they would be designated “Q” in ISO 3183.

The development of seamless ultra high strength pipe is at present understood to be the initiative of one company only so cannot be considered further in this paper.

Metallographic Structure of Ultra-High Strength Linepipe

The following generalized descriptions of microstructure are of X100 material and are probably similar to X90 steel. Alternative X100 steel compositions within the broad envelope allowed by ISO DIS 3183 may result in different forms of microstructure and it is not possible to categorise all from data presently available. No details of X120 microstructures are available for this paper.

The base metal microstructures of pipes from different manufacturers will exhibit slight variation according to the steel composition and plate rolling process used but typically range from a mixture of polygonal ferrite and bainite with a core grain size of ASTM 10/11 and slightly finer grain structure near the surface. Some pipes can exhibit predominantly bainitic structure, possibly with patches of martensite.

Seam weld microstructures are predominantly acicular ferrite with some bainite or MAC constituents.

The seam weld heat-affected-zone (HAZ) is of special interest in UHS steels and the phenomenon of HAZ softening which has been observed in several X100 pipes is generally consistent with the HAZ microstructures. The coarse grain HAZ microstructure is typically a relatively coarse aligned ferrite with MAC and bainite with a grain size of typically ASTM 4-5. The fine grain HAZ is typically very fine polygonal ferrite with some MAC constituents and bainite.

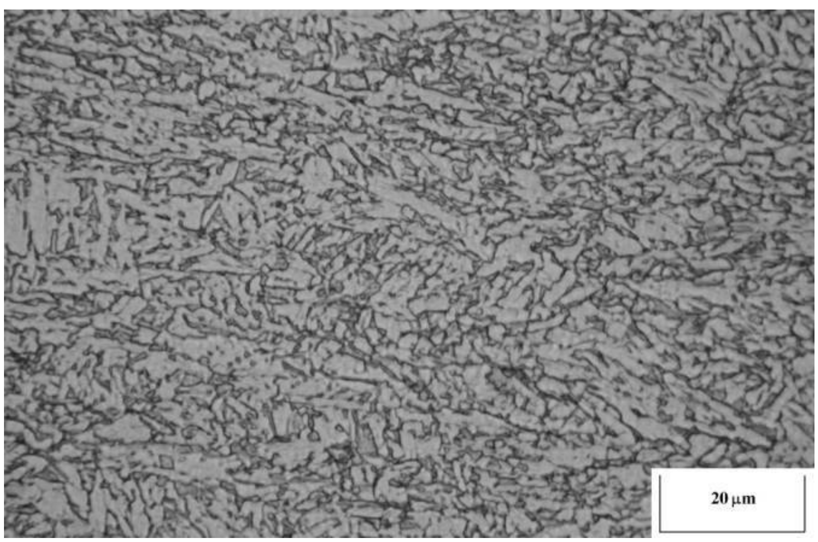


Figure 2 Microstructure of X100 Parent Metal

Tensile Properties

The tensile requirements proposed in ISO 3183 for high strength and ultra high strength linepipe are shown in Table V.

Particular attention should be paid to the proposed yield strength ranges for the UHS grades. At present the table shows a 150MPa (22ksi) range for X90 and X100, while for X100 the respective range is 220 MPa (32ksi). These ranges are similar to those for other grades and provide operational latitude for steel makers and pipe mills but may result in difficulties for users who need to specify weld metal for field girth welding with a yield strength that must overmatch the actual yield strength of the parent pipe. In any one order for UHS pipe, the actual yield strengths of pipes may easily span the allowed range and, if strengths increase above the permitted maximum, difficulties can result with girth welding.

Table V. Tensile Requirements for High Strength and Ultra-High Strength PSL 2 Pipe [6]

Pipe designation	**Pipe body of seamless and welded pipes**						**Weld seam of HFW, SAW, and COW pipes**
	Yield strength $R_{t0,5\ a)}$MPa (psi)		**Tensile strength** R_m MPa (psi)		**Ratio** $R_{t0,5}{}^{b}/R_m$ maximum	**Elongation on 50 mm or 2 in** A % minimum	**Tensile strength** R_m MPa (psi) Minimum
	minimum	maximum	minimum	maximum			
L450Q or X65Q L450M or X65M	450 (65 300)	600 (87 000)	535 (77 600)	760 (110 200)	0,93	b	535 (77 600)
L485Q or X70Q L485M or X70M	485 (70 300)	635 (92 100)	570 (82 700)	760 (110 200)	0,93	b	570 (82 700)
L555Q or X80Q L555M or X80M	555 (80 500)	705 (102 300)	625 (90 600)	825 (119 700)	0,93	b	625 (90 600)
L625M or X90M	625 (90 600)	775 (112 400)	695 (100 800)	915 (132 700)	0,95	b	695 (100 800)
L690M or X100M	690 (100 100)	840 (121 800)	760 (110 200)	990 (143 600)	0,97	b	760 (110 200)
L830M or X120M	830 (120 400)	1 050 (152 300)	915 (132 700)	1 145 (166 100)	0,99	b	915 (132 700)

a For grades > L625 or X90, $R_{p0,2}$ applies.

b The specified minimum elongation shall be as determined using the following equation: $A = C\dfrac{B^{0,2}}{U^{0,9}}$ where

A is the minimum elongation in 50 mm or 2 in, expressed in percent, rounded to the nearest percent;

C is 1 940 for calculations using SI units and 625 000 for calculations using USC units;

B is the applicable tensile test piece cross-sectional area, expressed in square millimetres (square inches), as follows:

U is the specified minimum tensile strength, expressed in megapascals (pounds per square inch).

Welding development trials showed only a limited available range of suitable GMAW welding wires which would produce deposits offering overmatching yield strength, high tensile ductility and toughness. API WG 4193 advised that the maximum yield strengths for X100 and X120 should be 825 MPa and 1025 MPa respectively. For Grade 690 (X100) this would align maximum yield strength values between ISO 3183 and CSA Z245.1.

Therefore, in the case of X100, a typical company supplementary specification may limit the maximum yield strength to values as shown in Table VI.

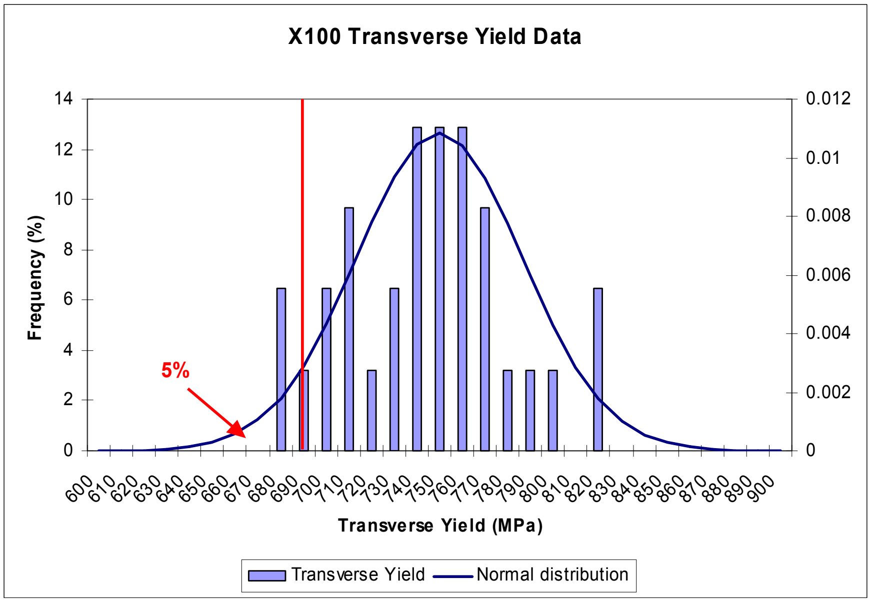


Figure 3. Distribution of Transverse Yield Strength in X100

Table VI. User Supplementary Purchase Specification (Transverse Tensile Properties)

Grade	**YS Min**		**YS Max**		**UTS Min**		**UTS Max**		**YS/TS**	**Elong**
	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	% max	%
X90	90	620	108	745	100	690	125	862	0.93	a*
X100	100	690	117	810	110	760	130	900	0.95	a*

*The minimum tensile elongation "a" shall be determined according to the SI Units Equation of API 5L Table 3B. The value of tensile elongation shall be recorded.

The measurement of yield strength in these higher strength steels has proved controversial as, if the flattened strap is used for tensile testing, the UHS steels suffer from a pronounced Bauschinger effect. The resulting recommendation is therefore that transverse direction tensile tests are made on cylindrical or prismatic test pieces, machined from unflattened material. This type of test piece will give a more accurate value of yield strength than the flattened strap as it is taken from within the wall of the pipe, it will sample more of the central material of the wall and less or none of the material immediately below the surface of the pipe. Thus, it will not sample skin-effects which may consist of more heavily worked material.

Yield Ratio

There is conjecture about the yield ratio limits proposed for the ISO standard for the UHS steels and as can be seen in Table V, the values of 0.97 for X100 and 0.99 for X120 have attracted adverse comment. In API 5L, the yield/tensile ratio is not specified but in some European countries, low limiting yield/tensile ratio values are mandatory requirements in statutory regulations, albeit based on historical practices with different types of steel. The YS/TS ratio should be reviewed along with the tensile stress-strain curve for each material and it is well established that the stress-strain curve for modern low carbon-microalloyed, TMCP processed, UHS steels is very different from traditional higher carbon normalised or as-rolled steels. The newer materials do not exhibit a pronounced yield point and the yield may, in fact be measured as either as $Rp_{0.2}$ (0.2% offset) or $Rt_{0.5}$ (0.5% total strain). The post yield work hardening in these steels is rarely accompanied by a significant rising load but is usually characterised by a considerable amount of post yield uniform extension prior to failure.

It is in the transverse direction that the yield/tensile ratio values can approach unity; the corresponding values in the longitudinal direction being considerably lower. Figure 4. Care should be exercised in specifying high strength steels to ensure that the required properties are achieved in the delivered coated condition (strain ageing may occur during coating as a result of the pipe forming strains).

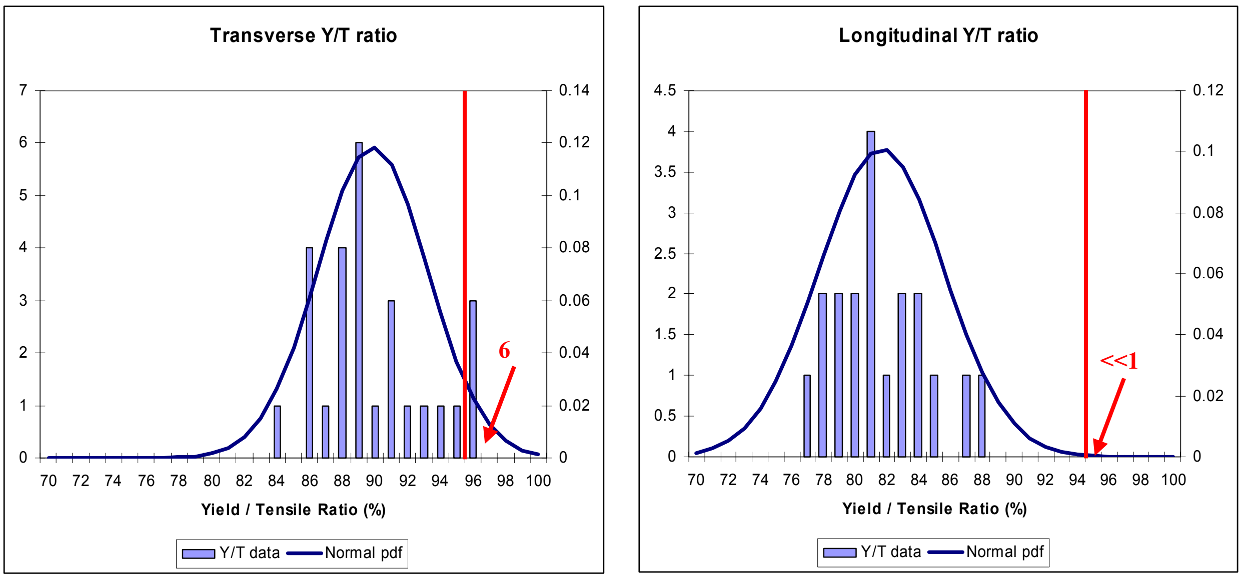


Figure 4. Comparison of X100 Yield to Tensile Ratios in Transverse and Longitudinal Direction

Longitudinal Tensile Properties of UHS Pipe

The plate rolling/processing and subsequent pipe manufacture create considerable anisotropy in the UHS pipes which is manifested in the longitudinal tensile properties being lower than those in the transverse direction. This aspect is not covered in DIS 3183 and the user should take this into account when ordering UHS pipe as, in certain instances e.g. pipe-lay in arctic regions of "unstable permafrost" or in other areas of uncertain foundation for the pipeline, longitudinal direction properties will assume greater importance. This is probably not an item that can be standardised and is likely to remain a matter for negotiation between purchaser and pipe mill with longitudinal properties measured "for information". Table VII provides a general indication of the lower longitudinal direction properties and Figure 5 indicates a typical distribution of longitudinal yield strength values in X100.

Table VII User Supplementary Purchase Specification
(Longitudinal Tensile Properties)

Grade	**Yield Strength Minimum**		**Yield Strength Maximum**		**UTS Minimum**		**UTS Maximum**		**YS/TS**	**Elongation on 50.8 mm or 2" GL**
	ksi	MPa	ksi	MPa	Ksi	MPa	ksi	MPa	%	%
X90	84	580	102	705	100	690	125	862	0.93	a*
X100	87	600	105	720	110	760	130	900	0.95	a*

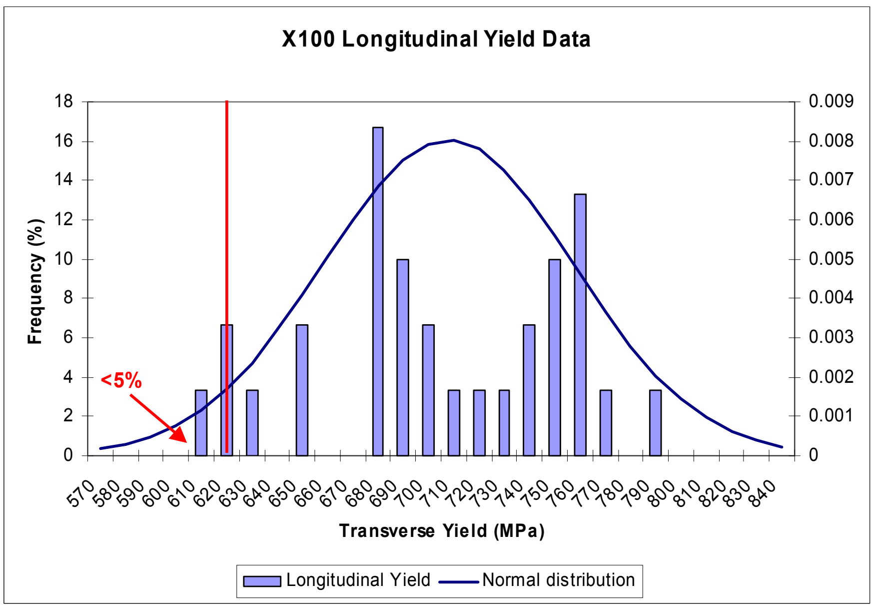


Figure 5. Distribution of Longitudinal Yield Strength in X100

Toughness

The minimum toughness values (for fracture initiation resistance) in UHS grades of linepipe have been included with other PSL 2 grades in ISO DIS 3183. Table VIII

Table VIII Charpy Requirements for Pipe Body of PSL 2 Pipe [7]

Specified outside diameter *D* mm (in)	**Full-size CVN absorbed energy, minimum** *KV* J (ft·lbf)						
	Grade						
	≤ L415 or X60	> L415 or X60 ≤ L450 or X65	> L450 or X65 ≤ L485 or X70	> L485 or X70 ≤ L555 or X80	> L555 or X80 ≤ L625 or X90	> L625 or X90 ≤ L690 or X100	> L690 or X100 ≤ L830 or X120
≤ 508 (20.000)	27 (20)	27 (20)	27 (20)	40 (30)	40 (30)	40 (30)	40 (30)
> 508 (20.000) to ≤ 762 (30.000)	27 (20)	27 (20)	27 (20)	40 (30)	40 (30)	40 (30)	40 (30)
> 762 (30.000) to ≤ 914 (36.000)	40 (30)	40 (30)	40 (30)	40 (30)	40 (30)	54 (40)	54 (40)
> 914 (36.000) to ≤ 1 219 (48.000)	40 (30)	40 (30)	40 (30)	40 (30)	40 (30)	54 (40)	68 (50)
> 1 219 (48.000) to ≤ 1 422 (56.000)	40 (30)	54 (40)	54 (40)	54 (40)	54 (40)	68 (50)	81 (60)
> 1 422 (56.000) to ≤ 2 032 (80.000)	40 (30)	54 (40)	68 (50)	68 (50)	81 (60)	95 (70)	108 (80)

The approach is considered by some to be controversial in that the minimum Charpy energy requirement is related to diameter and grade of pipe. As can be seen from the table, the requirements for smaller diameter pipes, even at Grades X100 (L690) and Grade X120 (L830) are modest at 40J (30 ft.lbs) respectively. However, much higher energy values, typically 95 J (70 ft lb) and 108 J (80 ft.lb) are required in the same pipes when supplied at larger diameters.

This follows a similar approach to that adopted in EN 10208-2 and ISO 3183-2: 1996 in which similar tables were used to specify Charpy requirements for the arrest of running fracture for specific design conditions, relating to the European gas distribution industry. Although the purpose of this table is different in the current DIS 3183, it allows the pipe manufacturer the advantage of standardising the test at 0°C (32ºF) unless the purchaser and vendor agree that an alternative test temperature should be used. The specified impact energy values are reinforced with a further requirement that the Charpy fracture shear area for each test at 0ºC should be at least 85 percent. The same shear area criterion can be applied to tests at a lower temperature if agreed between purchaser and the pipe mill.

Although the API/ISO working group reviewed the requirement and considered that such tests, on full size Charpy specimens, will provide sufficient fracture resistance for most pipeline designs, the approach is not without its critics who contend that the effect of wall thickness is not adequately addressed. The alternative, which was not adopted, would have been to relate the Charpy test temperature to the minimum design temperature for the pipeline for which the pipe is being purchased, as follows. Table IX.

Table IX Charpy Test Temperature vs Thickness for Avoidance of Brittle Fracture [8]

Specified Wall Thickness T, mm	**Test Temperature [a, b)] °C**
T ≤ 20	TD - 10
20< T ≥ 30	TD - 20
T > 30	TD – 30
a TD: Design temperature as stated in the enquiry and order b Other temperatures may be agreed between purchaser and supplier	

This was not adopted as pipe mills considered that testing each mill order at a different temperature does not assist their compilation of a production data base of Charpy values. However, this format of specifying the test may feature in user supplementary purchase specifications.

In the testing of UHS steels, X100 base metal has consistently given high Charpy energy values even at temperatures down to minus 50°C (Figure 6) confirming that values specified in DIS 3183 are readily achievable.

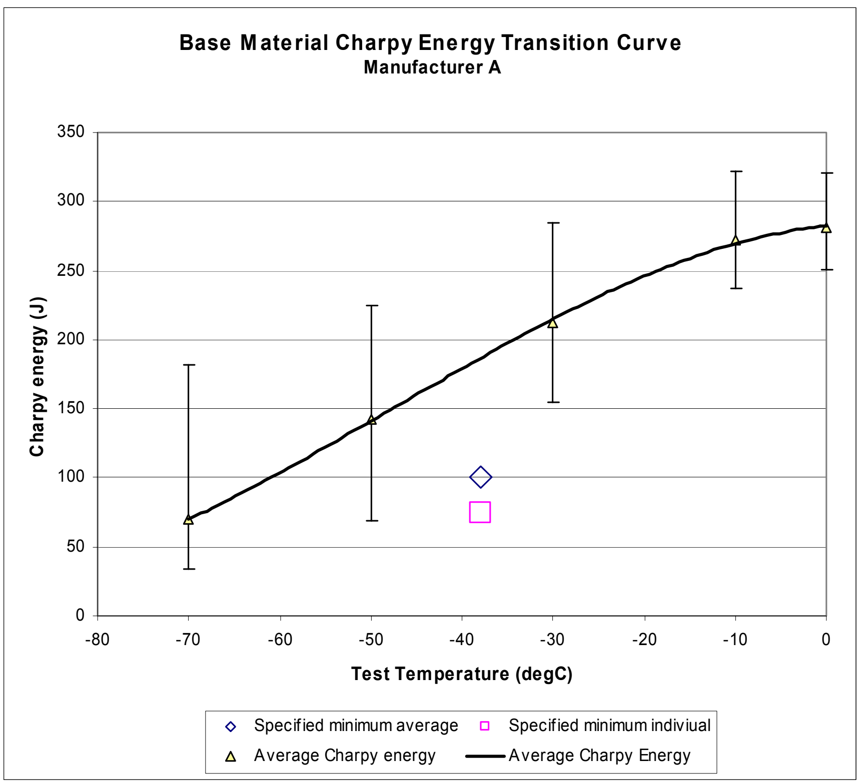


Figure 6 Typical Base Metal Charpy Transition Curve for X100

Drop Weight Tear Test (DWTT)

ISO DIS 3183 also specifies Drop Weight Tear Test (DWTT) for PSL 2 welded pipe including the UHS grades. Again, the test temperature is specified as 0ºC (32ºF) unless a test at a lower temperature is specified. The standard requires a minimum shear fracture area of 85 percent but where the purchaser specifies a lower DWTT test temperature, acceptance criteria may have to be negotiated.

Annex G for Gas

ISO DIS 3183 contains an extensive informative Annex G specifying additional provisions that apply to PSL 2 pipe that can be Charpy impact tested and is ordered with resistance in the pipe body to running fracture propagation in gas pipelines. The annex contains five alternative approaches to testing and selection of acceptance criteria and, once an approach has been selected it becomes normative. The five alternative approaches allow methods used traditionally in various areas of the word to continue to be applied. The approaches are:

1 Use of The European Pipeline Research Group (EPRG) Guidelines for fracture arrest. The result of extensive test work by EPRG is translated into three tables relating minimum Charpy energy requirements, diameter and grade of pipe and individual design factor for the pipeline. The tests relate to lean gas and cover the pipe grades up to X80 (L555). Further work on X100 is currently in progress in Europe. [9-10]

2. This approach uses the Battelle simplified equation based on the two curve approach and is suited to natural gas mixtures that exhibit single phase decompression behaviour at operating pressures up to 7.0 MPa (1015 psi). It applies to grades up to X80 (L555) only.

3 The third approach is also based on the Battelle two-curve approach and in conjunction with a PRCI report is appropriate to fluids exhibiting single-phase decompression behaviour and for rich gases that decompress into the two phase boundary for operating pressures up to 12.0 MPa (1740 psi) and for grades up to X80 (L555)

4 The fourth approach is based on an equation that is statistically fitted to the full scale burst test data of AISI. This is limited to a range of test data against which it was originally calibrated, typically X70 (L 485), diameter less than 48” (1219 mm) and a maximum wall thickness of 18.3 mm.

5. This is the approach that is considered to be currently applicable to the UHS grades of pipe X90 (L-625) through X120 (L830). It is based on full scale testing to validate the arrest toughness for a specific pipeline design, fluid and temperature. Typically, a range of pipe toughness is installed in the burst test section with the pipe toughness increasing on each side of the starter fracture initiation pipe. The pipeline specific gas composition, temperature and pressure level are used for the burst test. Extensive evaluation is carried out on data recorded from the burst test and on the fractured pipe. Tests of this type have been conducted on the UHS linepipe grades (Figure 7) and this approach will continue to be used for new pipeline projects until sufficient data has been amassed to enable running fracture arrest toughness to be predicted and extend existing theoretical models.

Welding, Forming and Bends

It is outwith the scope of this paper or the ISO and API line pipe standardisation working groups to deal with welding and forming of the UHS pipes or the provision of factory made bends.

However, extensive work has been conducted [12, 13] to develop fast, economic and robust field welding procedures for X100 and X120 product Figure 8, and to categorize the field bending behaviour of such pipe, Figure 9. These efforts have contributed to sufficient confidence in the products to encourage standardisation of the linepipe.

Factory production of fabricated or induction bends and other fittings to match the UHS properties has lagged the development of the pipe but is an issue that must be addressed if construction exclusively in these materials is to be achieved. In the meantime, bends and fittings up to the maximum strength available typically X80 (L555) can be used, albeit with thicker scantlings, in conjunction with UHS pipe.

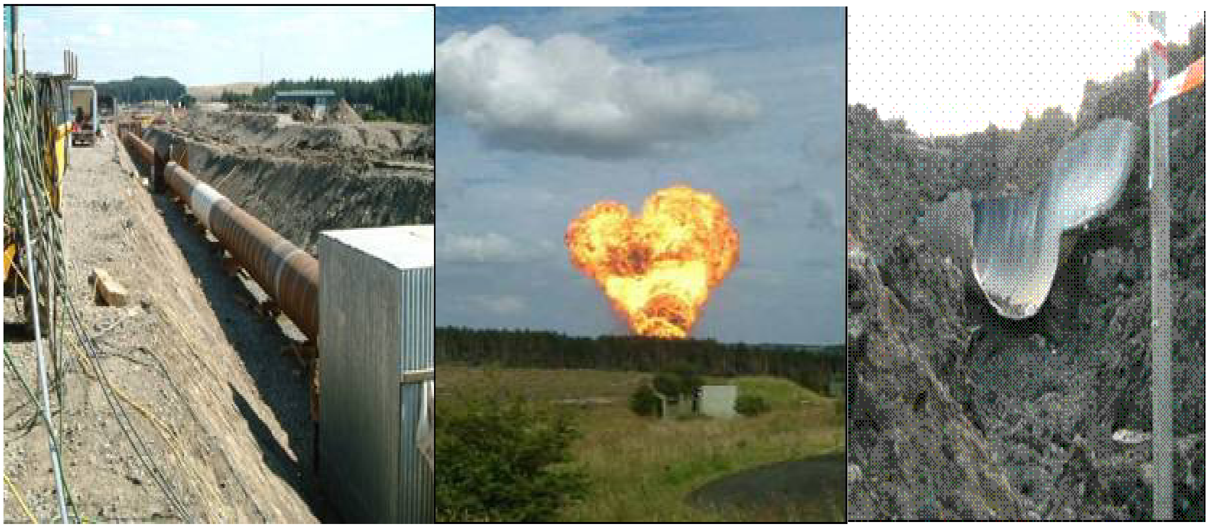


Figure 7. Construction of a fracture control test, detonation to initiate a running fracture and section of X100 pipe after test

Figure 8. Development of rapid field welding by GMAW for X100

Figure 9. Field bending trials on X100 line-pipe

Conclusion

A decade of collaborative development between the oil/gas and steel pipe industries has resulted in three new high strength grades of line pipe being brought to market. These are X100 (L690) and X120 (L830) and through the X100 programmes, a third lower strength material X90 (L 625).

As with any new grade of pipe, experience grows with the manufacture of each order but the extensive testing and evaluation of these materials and industry collaboration has allowed the process of standardisation to begin. Accordingly, these grades have been presented to ISO and API for inclusion in a new ISO Standard 3183 and, by a process of harmonisation, into a future API 5L. One grade L690 (X100) has already been standardised in Canadian Standard CSA.Z245.1

At present these grades are available only as large diameter submerged arc welded pipe aimed at a market for high pressure, long distance gas transmission pipelines but other developments may lead to ultra high strength weldable seamless pipe which has a potential market in deepwater offshore oil and gas exploitation.

The primary basis of these high strength pipes are low carbon, micro-alloyed steels which are rolled to plate using TMCP methods to produce steels having fine ferritic-bainitic microstructures, generally high toughness and weldability.

Continuing use of these materials and further evaluation programmes will provide more data which will facilitate progressive revision of standards with time

The present stage of standardisation of the ultra-high strength materials is similar to that for many lower grades of linepipe in present API and ISO standards and represents the best consensus that can be obtained between steel makers, pipe-mills and users. As a result if this, most purchasers will be obliged to table project-specific technical supplements to the base specification when enquiring ands ordering pipe.

In the all important area of running fracture arrest in gas pipelines, existing models have not yet been fully validated for these high strength grades, so for the foreseeable future, gas companies may have to conduct fracture control (burst) tests to determine if the high strength pipe toughness is sufficient to arrest a running fracture or if the intended pipeline will need to build in crack arrestors at specified intervals.

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[4] BP Exploration. Private Communication

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