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SMALL DIAMETER X70 AND X80 LINEPIPE FOR HIGH PRESSURE GAS TRANSMISSION

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Keywords: ERW pipes, alloy design, weldability, fracture control, defect acceptance

Abstract

The Australian natural gas transmission system is characterized by relatively small markets for gas located at long distances from the sources of supply. The need to deliver gas to these markets at internationally competitive energy costs in competition with other fuels has led to the development of unique ERW pipeline designs comprising:

- a relatively high design pressure of 15MPa compared to 10MPa or less that is characteristically used in most parts of the world;
- the transmission of rich gas which places special demands upon fracture toughness;
- small diameter typically 18" (DN450);
- high strength levels typically X70 moving to X80;
- relatively thin wall thickness; and
- an expected move from 72 to 80% design factor.

The needs generated by these design parameters have stimulated developments in steel making and hot strip production to achieve sufficient strength, weldability and toughness suitable for ERW pipe production. Parallel developments have also occurred in girth welding, control of HACC without preheat at very high production rates, girth weld defect tolerance, and other areas relevant to pipeline construction and operation.

Introduction

Over the last twenty years in Australia, the "standard" pipe grade has moved from API 5L X52 through to the present API 5L X70 with maximum operating pressures rising from 6.8 MPa to 15.3 MPa. These changes have been driven by the economic benefits of higher strength pipelines such as lower gas transportation costs, lower pipe procurement and transport-to-site costs and reduced welding costs due to smaller diameter and thinner wall. In Australia, X70 was supplied to a high-pressure gas transmission project for the first time in 1993 and since then BlueScope Steel has supplied nearly 400,000 tonnes of X70 skelp feed for many major domestic pipeline projects. The importance of achieving high strength in pipes without compromising field weldability was a major focus in the development of X70 grade ERW pipes and also laid the foundation for X80 grade development. Although no Australian pipelines have yet been designed in X80 grade, a demonstration segment (~2000 tonnes) was incorporated into an X65 Queensland looping line project in 1999. This paper outlines some aspects of the product development that has taken place for grades X70 and X80 at BlueScope Steel in response to market requirements over the past decade. It also summarises the various research activities that have been undertaken in Australia to pave the way for the use of X80 grade and also to permit a move towards upgrading the design factor from 72 to 80% in high strength small diameter thin walled pipes.

Pipeline Steel Design for X70 and X80

The challenge of achieving demanding pipe mechanical properties within the industry prevailing requirements of preheat free welding with cellulosic electrodes and other technical challenges (such as the requirement for high Charpy energy values to permit rich gas transportation and a low pipe yield strength range of less than 100 MPa above SMYS) has required careful attention to alloy design and thermomechanical processing (TMCP) issues. The broad approach taken by BlueScope Steel in the technical solution for X70 and X80 has been described in detail elsewhere[1]. A key strategy has been the use of the Mo-Nb-Ti microalloying system so as to achieve high pipe strength more comfortably at lower carbon equivalents compared to traditional Nb-V steels. Some important alloy design and TMCP aspects supporting the achievement of high strength in Mo-Nb-Ti steels for X70 and X80 ERW linepipe are briefly outlined below:

Alloy Design

The Mo-Nb-Ti microalloying system has proven to be very effective in achieving the strength requirements of X70 and X80 pipes particularly in heavier wall thicknesses. The Nb-V steels require relatively higher carbon equivalent designs which can compromise their capability for preheat-free field welding with cellulosic consumables according to the guidelines specified in WTIA Technical Note 1 Recommendations[2]. This weldability benefit is evident in Figure 1 which depicts typical average production data for some major projects over recent years. Typical chemical compositions supplied to various projects are summarised in Table 1.

Table 1. Typical Chemical Compositions of X70/X80 ERW High Strength Linepipe Steels

Steel	API Grade	Chemical Composition, Mass %												CEQ (IIW)(1)	Pcm(2)
		C	Mn	Si	P	S	Al	Nb	V	Mo	Ti	N	Ca		
A	X70	0.085	1.50	0.32	0.015	0.001	0.030	0.045	0.050	-	0.013	0.0045	0.0008	0.36	0.18
B	X70	0.095	1.55	0.32	0.015	0.001	0.030	0.040	0.060	-	0.013	0.0045	-	0.37	0.19
C	X70	0.060	1.35	0.32	0.013	0.003	0.030	0.060	-	0.23	0.014	0.0050	0.0008	0.34	0.16
D	X70	0.070	1.50	0.32	0.012	0.005	0.030	0.060	-	0.11	0.015	0.0050	0.0008	0.34	0.17
E	X70	0.075	1.20	0.26	0.013	0.003	0.034	0.059	-	0.10	0.020	0.0045	0.0007	0.30	0.16
F	X70	0.075	1.40	0.34	0.010	0.002	0.033	0.063	-	0.10	0.020	0.0047	0.0008	0.34	0.17
G	X80	0.075	1.59	0.31	0.018	0.001	0.026	0.057	-	0.22	0.013	0.0060	0.0011	0.38	0.18
H	X80	0.067	1.54	0.32	0.012	0.002	0.030	0.069	-	0.28	0.019	0.055	0.0010	0.39	0.18

Some other aspects of the alloy design include the use of Ca for globular complexing of alumina inclusions (pipe UST performance), and micro-Ti additions for enhanced weldability (reduced HAZ hardness[3] and resistance to HAZ cold cracking[4]). The main structural factors contributing to the enhanced strengthening in Mo-Nb-Ti steels (in comparison to Nb or Nb-V steels) are summarised below:

i) a significantly finer (often irregularly shaped) ferrite grain size, typically being about 2.5 or 2.0 µm in X70 and X80 steels respectively. These ferrite grains are also characterised by an extensive network of sub-grains.

ii) low temperature transformation products substantially replace pearlite, mainly bainite containing acicular carbide needles in the lower Mn–Mo-Ti X70 steels and martensite/ austenite

(MA) regions in the more highly alloyed X80 steel.

iii) enhanced precipitation hardening from the Mo-Nb-Ti system. A synergistic benefit of Ti on the strength of the Mo-Nb system (even below the stoichiometric ratio with N when TiC strengthening would not be expected) is apparent from the data of Figure 2. It is thought that the addition of Ti promotes more efficient precipitation strengthening of ferrite in Mo-Nb steels. The removal of nitrogen as TiN would encourage the precipitation in ferrite of Nb carbide rather than Nb nitride. More precipitation hardening of ferrite should thus be possible because the carbide is more soluble in austenite than the nitride. Alternatively or in addition, the possibility of forming ultra fine (Ti,Mo)C has been recently reported[5] as a significantly more efficient strengthening species in ferrite than TiC. Such particles could be co-existing or complexed with Nb(C,N).

Thermomechanical Processing, Strength and Microstructure

Proper control of the entire rolling process from slab reheating to coiling is essential to develop the appropriate strength (and fracture toughness) requirements. In addition, there is a growing emphasis from pipeline operators for a controlled range of pipe strengths, such as SMYS + 100 MPa. The reason for this is to ensure overmatching strength of girth weld metal to provide adequate protection of weld metal defects in the event of longitudinal in-service displacement of the pipe in regions of unstable terrain. As will be discussed later, overmatching the strength of weld metal is more difficult to achieve in higher strength pipe given the industry expectation in Australia for field welding with cellulosic electrodes. Whilst able to deliver higher strength welds, mechanised welding has not yet proven to be an economically viable alternative to manual girth welding of thin walled pipes. For these reasons alloy design and key rolling

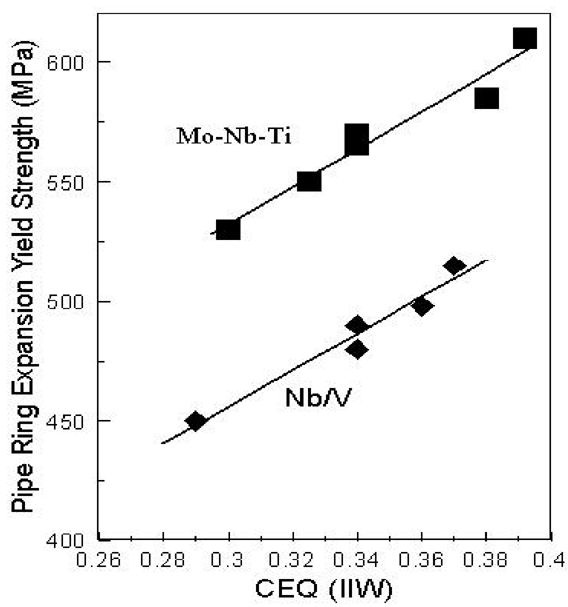


Figure 1. Relative strengthening capacity of Mo-Nb versus Nb/V microalloying systems

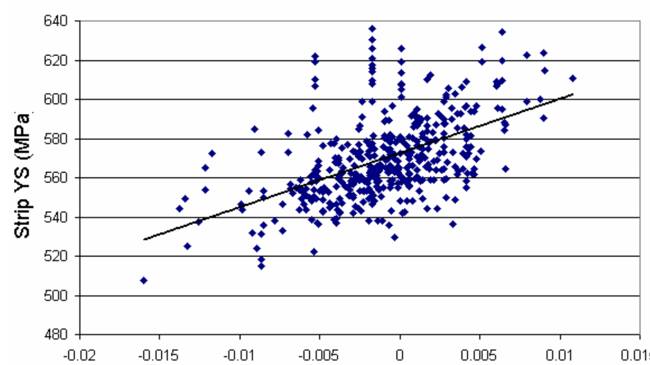


Figure 2. Effect of Free Ti (not as TiN) on Strip YS of Mo-Nb X70 steels (Free Ti =0 when %Ti =3.4 x %N)

parameters need to be optimised to ensure a controlled range of strength in the hot strip. For Mo-Nb-Ti steels, the steel composition and prior thermomechanical history will determine the hardenability prior to cooling start. The final strip properties are essentially controlled by the manner in which the strip-cooling curve (which depends on such factors as the selection of spray banks applied, strip thickness and rolling speed) intersects the deformation CCT diagram (Figure 3). If rapid cooling on the runout table is applied prior to the start of transformation, the strength may be enhanced by undercooling of the austenite to ferrite transformation which promotes grain refinement, and increased volume fraction ratio of acicular to polygonal ferrite phase (AF/PF)[6].

For low CEQ Mo-Nb-Ti steels such as those shown in Table 1, the microstructures generated in hot strip rolling can show a variation in the relative volume fractions of component phases through the strip thickness[6]. Generally speaking, a decreasing volume fraction of acicular and MA phases from strip surface regions (as well as an increase in grain size) towards the strip centre is observed particularly for thicker strips. This behaviour reflects the relatively low hardenability of these steels so that hardenability drivers such as Mo level, % austenite non-recrystallising reduction, FRT(finish roll temperature)-Ar3 and cooling rate can significantly influence the strip strength. Additionally, balancing the cooling intensity from top to bottom of the strip will ensure that the strip strength is not compromised by a softer bottom surface region. The effect of increasing %MA (which is accompanied by an increasing ratio of acicular to polygonal ferrite) on strip strength of X80 grade for different strip rolling conditions is shown in Figure 4. Low FRT and high % non-recrystallising reduction in austenite tend to diminish the strength of Mo-Nb-Ti strip due to reduced austenite hardenability. Conversely, higher FRT and lower non-recrystallising reduction eventually reduces strip strength because of coarser transformation structures inherited from the resultant larger austenite grain sizes. However, strip strength variations for these steels have proven to be rather small in the range of finish rolling and cooling parameters normally selected for production conditions. This makes Mn-Nb-Ti steels ideally suited to the achievement of narrow strength ranges across large project orders.

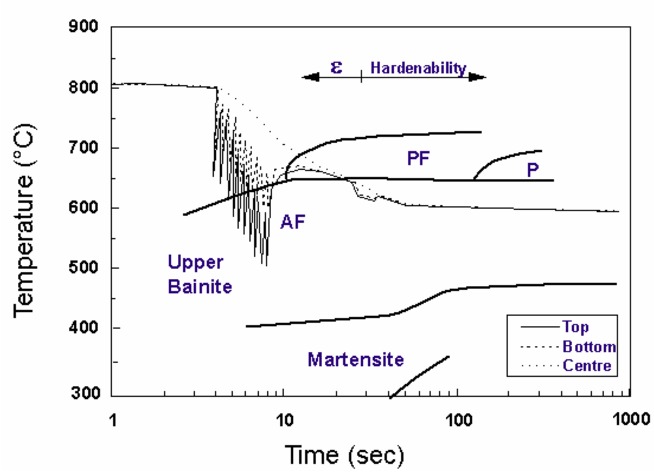


Figure 3. Deformation CCT Curve for X80

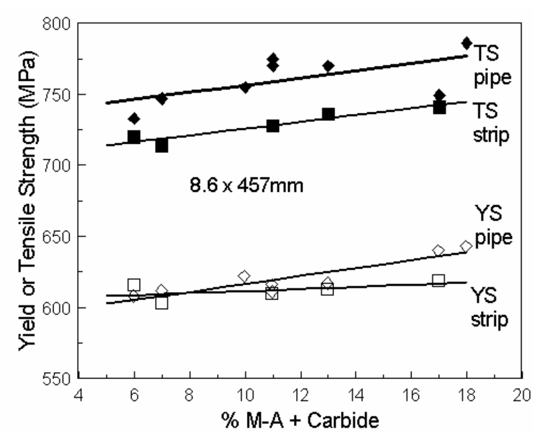


Figure 4. Effect of % M-A on strength of X80 strip and 8.6 x 457mm pipe

Pipe Properties

When the hot rolled strip is converted into ERW pipe, the pipe-forming and sizing strains can significantly modify the pipe yield strength by virtue of the Bauschinger effect and work hardening behaviour[7]. Material factors such as steel composition and microstructure (ratio of AF/PF, %MA, grain size etc), Luder's elongation and pipe processing factors (eg. the level of forming strain, t/D; pipe mill fin-pass and sizing set up, etc) contribute in a complex manner to this strength change. Some indications of these changes are evident in Figure 5[8]. For a given steel type and pipe size, the strength loss from strip to pipe generally increases with increasing strip strength thus warranting major consideration in the design of higher strength grades such as X70 and X80. During the initial development of X70 and X80 grades, the limitations of utilising more stringent rolling schedules (eg. finish rolling temperatures just below Ar3 temperature) to increase strip yield strength and, pipe strength to X80 levels, proved an inappropriate approach particularly for the case of conventional Nb-V steels. As evident from Figure 6, lowering the finish rolling temperature below the Ar3 temperature was effective in significantly increasing the strength of the hot strip. However, almost no further improvement in the corresponding pipe strength was recorded suggesting that two-phase rolling exacerbates the Bauschinger drop. This "diminishing returns" effect led to the consideration of molybdenum additions as a means for more comfortably reaching the higher strength levels required for X70 and X80 pipes. It is evident from Figure 6 that higher pipe strength levels for Mo-Nb-Ti steels (at a given strip strength level) are due in part to the lower Bauschinger drop. The level of the Bauschinger drop in various Mo-Nb-Ti steels, for a given pipe t/D, is clearly controlled by the Luder's elongation as shown in Figure 7. The importance of microstructural factors in this behaviour has been suggested in Figure 4 and underlines the critical interrelation of alloy design and thermomechanical processing factors. Whilst achieving a narrow range of strip strength is important for the reasons mentioned above, achievement of the targeted value for the average of the population is also critical in order to meet the requirements for all resultant pipe to be in a range of SMYS +100 MPa. Careful design and control of the steel chemical composition and an intimate knowledge of the effects of rolling parameters are thus indispensable when it comes to achieving a tight control of strip strength.

At BlueScope Steel, this is achieved by the use of empirical predictive strength equations. In addition, a large history database for property shifts from strip to pipe at the pipe-mill has provided assurance that the Bauschinger effect can be confidently predicted for the various pipe manufactured sizes. Whilst variation in pipe forming conditions can cause scattering of the strip to pipe strength shift from rolling to rolling, the inherent corrective nature of the Bauschinger effect generally operates to produce a narrower range of strength than was produced in the original strip population. For example, coils with strength at the top end of the strength population have a natural tendency to undergo a greater Bauschinger strength drop than coils with lower strength. Overall, the accuracy of these empirical equations has proven to be more than adequate to achieve the required level and range of strip and pipe strengths. This has obviated the need for more complex fundamentally based metallurgical and non linear neural networks models that have occupied many researchers over the past decade[9]. An example of the excellent predictive capability of BlueScope Steel's simple empirical models is shown in Figure 8 with the achieved pipe strength ranges for various X70 projects shown in Figure 9. Combined with a knowledge of strength changes during pipemaking, this empirical model has enabled BlueScope Steel to comfortably achieve demanding specified strength ranges for skelp, such as 90% of pipe yield strength values falling in the range of SMYS+100 MPa (Figure 9). Further examples of typical strip and pipe properties obtained for various X70 and X80 projects and pipe sizes are shown in Table 2. Application of the Mo-Nb-Ti alloy system to the development and production of large quantities of X70 and trial quantities of X80 ERW pipe has given excellent results to date from both steel property and pipeline construction aspects.

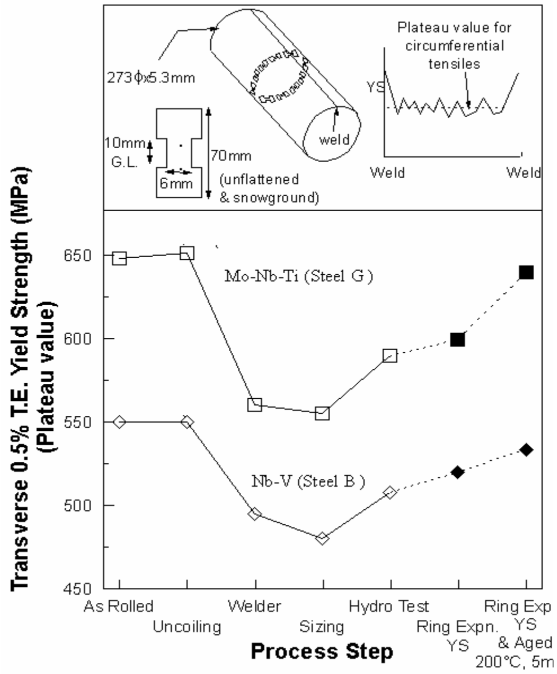


Figure 5. Changes in yield strength at various stages of pipe production.

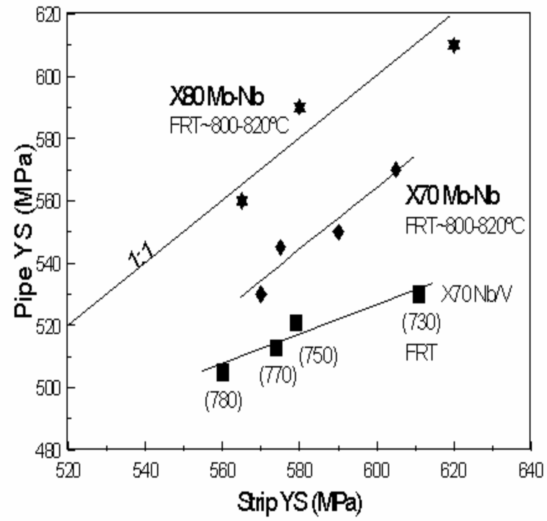


Figure 6. Bauschinger effect: Nb-V versus Mo-Nb Steels

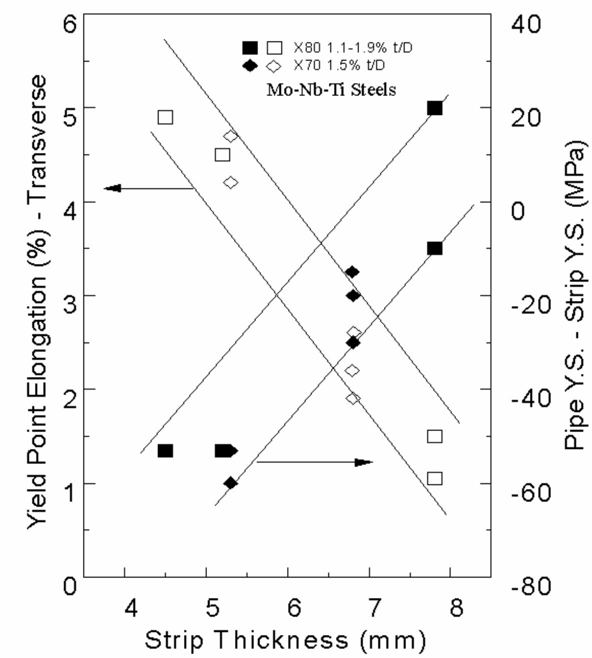


Figure 7. Relationship among yield point elongation, strip thickness, and Bauschinger drop

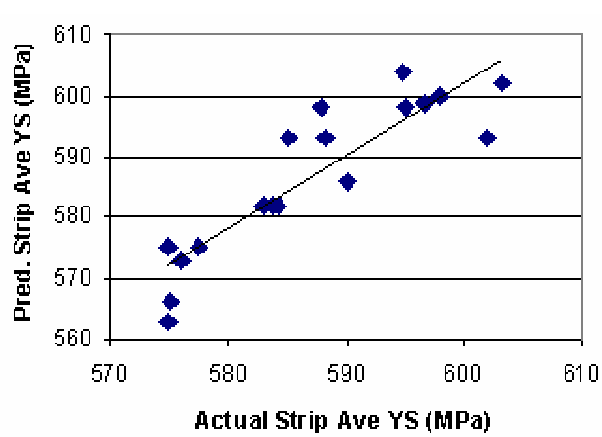


Figure 8. Predicted vs actual YS using empirical models for 19 major X70 projects (Mo-Nb-Ti steels) with sheet thickness in range of 4.8-9.7mm

Table 2. Typical Mechanical Properties for X70/X80 ERW Pipe Steels

Steel	Strip Thick. (mm)	Strip Mechanical Properties: Tensile (Trans.) LYS (MPa)	TS (MPa)	El. (%)	BDWTT 85% FATT (°C)	Charpy V-Notch Toughness: Spec'n Size (mm)	Test Temp. (°C)	En. (J)	50% FATT (°C)	Pipe Tensile Properties: Pipe Dia. (mm)	Ring Expan. YS (MPa)	TS* (MPa)
X70 Steel B	8.5	570	625	37	<-70	10 x 6.7	10	130	-110	406	498	630(T)
X70 Steel C	6.9	590	650	31	<-70	10 x5	-20	66	<-100	355	550	660(T)
X70 Steel D	9.6	560	642	34	-	!0 x 7.5	-15	143	<-75	355	550	660 (T)
X70 Steel E	5.3	570	615	34	<-70	10 x 5	0	84	<-100	355	530	620(T)
X70 Steel F	8.6	573	656	32	-	10 x 6.7	-15	102	-	323	566	662 (T)
X80 Steel G	5.2	650	692	30	<-70	10 x 5	-	-	-	273	600	-
	7.8	590	677	31	<-70	10 x 7.5	-15	124	<-110	406	585	-
	8.6	580	670	31	<-70	10 x 6.7	-15	110	<-100	457	590	710(T)
	9	579	673	34	<-70	10 x 7.5	-15	133	<-100	273	570	-
X80 Steel H	8.6	620	725	29	<-70	10 x 6.7	0	110	<-100	457	610	770(T)

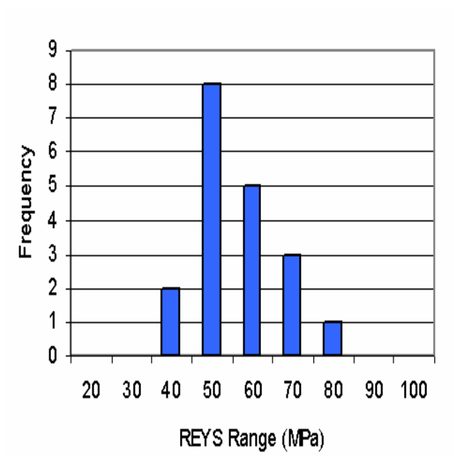


Figure 9. Range of ring expansionYS for 19 major X70 projects (range is for 90% of all test results); t: 4.8-9.7mm, dia:324-457mm

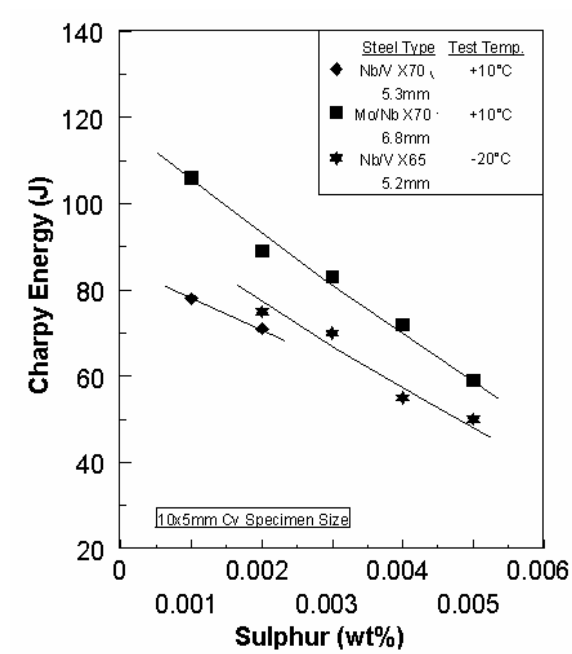


Figure 10. Effect of sulphur on Charpy impact toughness of API X65/X70 Steel types.

Fracture Toughness

Resistance to both brittle and ductile fracture propagation are prime requirements for linepipe steels. Modern low carbon alloy designs combined with the high non-recrystallising deformation levels and the high cooling rates achievable on hot strip mills ensure the base strip and accordingly pipe body has an extremely high resistance to brittle fracture. Typically the Charpy 50% FATT and the Battelle DWTT 85% FATT are lower than -100°C and -60°C respectively, Table 2. Accordingly, most attention is given to ensuring the appropriate level of toughness for resistance to ductile fracture propagation which is effectively a specification minimum for Charpy upper shelf energy. The Charpy upper shelf energy is primarily controlled via the sulphur and carbon levels while the hot rolling conditions can also contribute. The effect of the sulphur content on the Charpy toughness for Mo-Nb-Ti X70 is shown in Figure 10.

In most instances with current low carbon, microalloyed, fine grained linepipe steels, the fracture toughness requirements to avoid ductile fracture propagation in pipelines transporting lean gas can be comfortably achieved in ERW API Grades X60 to X70 pipe with a 0.005% maximum sulphur requirement. In the case of pipelines required to transport 'rich' gas, higher levels of ductile fracture propagation resistance (Charpy energy) are sometimes being sought in the steel. This requirement arises from the lower decompression rate of 'rich' gas compared to methane. Together with the prospect of design factors being raised from 72-80% SMYS, and a coincident shift to higher strengths such as X80, questions are now being raised not only in regard to the required level of Charpy energy (and the relevance of the Charpy test for predicted values for full size specimens above about 100J[10]) but also as to the technical feasibility of producing steels with sufficiently high energy values. These issues are currently receiving the attention of the Australian pipeline industry and full scale pipe burst testing is being considered to help resolve the requirements for ductile fracture control.

A further limitation of the Charpy test concerns the conversion of upper shelf energy values between Charpy specimen sizes. In view of the pipe wall thicknesses commonly associated with small diameter ERW pipe, the Charpy specimen size is normally subsize. It has been found that for modern high toughness pipeline steels, the energy absorbed per unit ligament area decreases with decreasing specimen thickness[10]. Thus converting upper shelf energy values from a full size to a sub size specimen via a pro-rata calculation will overestimate the energy requirement. The use of experimentally determined conversion correlations should thus be considered in determining the appropriate values applying to sub-size specimens.

Field Weldabilty of High Strength Linepipe

The most critical requirements in the girth welding of high strength linepipe are the mutually competing factors of susceptibility to hydrogen assisted cold cracking (HACC) and sufficient weld metal strength to match the pipe[11,12,13]. Progression towards X80 grade pipe has thus challenged the continued use of conventional MMA welding process because of the high weld metal hydrogen contents and the limited strength range of cellulosic consumables. Figure 11 demonstrates the strength issue confronting cellulosic consumables in the welding of high strength linepipe. However despite these potential issues the overall risk involved in the application of X80 is considered to be low[14].

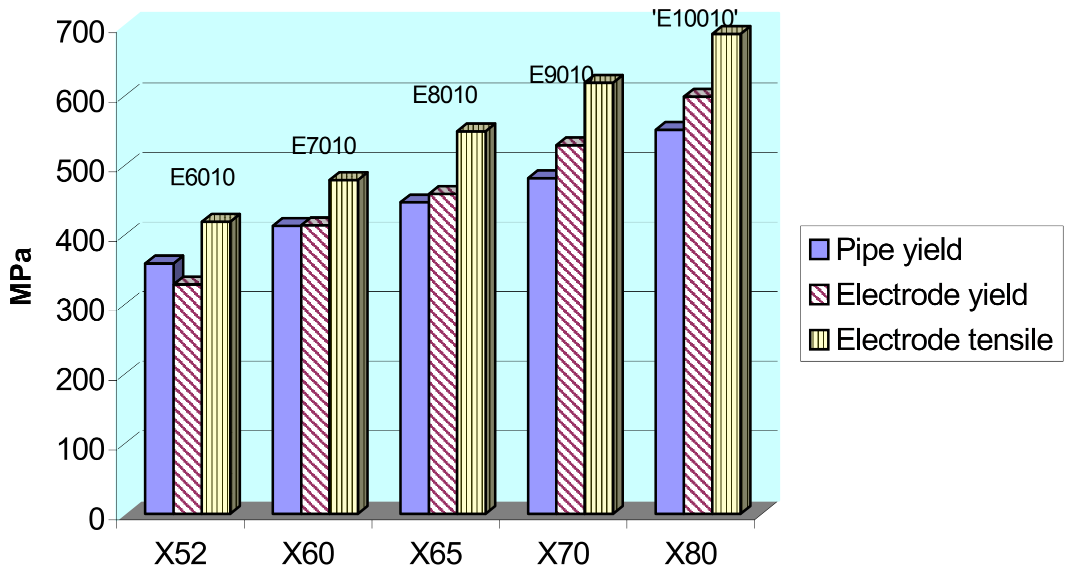


Figure 11. Comparative pipe and electrode strength levels. Note: The ‘E10010’ electrode is not available and shown for illustrative purposes only.

Hydrogen Assisted Cold Cracking

From a metallurgical viewpoint HACC, or cold cracking, is perhaps the most serious of all weld cracking problems. Cracking is associated with the accumulation of hydrogen at internal sites and is governed by the metallurgical structure, the presence of imperfections and the action of stress. Pipeline construction is a demanding process that imposes adverse conditions during the welding process that can increase susceptibility to HACC. These include high strength steel, lifting stresses during welding, and when cellulosic electrodes are used, extremely high levels of hydrogen.

It is imperative that girth welds be free from HACC over the range of essential welding variables because of the difficulties in finding cracks with conventional NDT, and because hydrogen cracking may occur sometime after NDT inspection. In short the prospect of cracking must be designed out of the welding procedure.

HACC has traditionally been an issue associated with the heat affected zone (HAZ) of the base pipe however with improved steel alloy design and advanced thermomechanical processing it is now more common to experience weld metal HACC. Although quantitative guidelines for weld metal HACC avoidance are yet to be established, considerable experimental data from laboratory tests such as the Welding Institute of Canada (WIC) [15] and the Rigid Restraint Cracking (RRC) [16] tests in conjunction with established field welding experience have defined conditions which limit the risk of occurrence to extremely low levels. These conditions are now incorporated in Australian Standard AS2885.2 – 2002.

Under normal field construction conditions where no more than two standard (18 metre) pipe lengths are lifted clear of the skids on a basically level right of way, the risk of HACC is considered remote provided that welding conditions are controlled and the pipe wall thickness is less than 10mm. These conditions are considered safe because the pipe wall thickness limitation restricts the weld cooling rate and imposed stresses. The appropriate timing of the hot pass which occurs within 8 minutes of completion of the root pass also provides considerable benefits which include :

- decreased weld cooling rate to increase time and thermal energy for hydrogen effusion,
- increased weld throat thickness and decrease stress concentration, and
- refinement of the root pass microstructure thus improving the fracture toughness.

Qualification of the weld procedures over the range of expected field conditions or under worst case conditions will confirm weld integrity while the essential variables defined in AS2885.2 will outline the broad boundaries which provide a safe operating window to minimise the risk of HACC (discussed later).

The greatest risk of the occurrence HACC is due to the tendency to increase field productivity beyond that which has been defined by the qualified weld procedure. Obviously there are significant economic benefits arising from early completion of the project. However changes to the weld procedure not only alter the metallurgical effects during welding but may also influence the level of imposed stress on the weld. Such conditions dramatically increase the susceptibility to HACC. Increased root pass weld speeds, and hence decreased weld heat inputs, can lead to rapid weld cooling rates and abnormal weld solidification structures [15]. Depending on weld metal impurity levels and weld joint stress, hot cracking has also been known to occur. Such cracking can itself generate significant longitudinal centre line cracks, and can serve as initiation sites for hydrogen cracks. Clearly there is a significant increase in risk of welding problems when unqualified modifications to the welding procedure occur.

In contrast to cellulosic electrodes, mechanised gas metal arc (GMA) welding systems produce very low levels of diffusible weld metal hydrogen and so are much less susceptible to HACC. In fact to the authors' knowledge there has never been an example of problems due to HACC in GMAW pipeline girth welds[17]. This is not to say that HACC is impossible, it is just much less likely. The problem that does arise with low weld metal hydrogen levels is that if HACC is generated, it would be expected to occur as much as 24 hours or more after welding. This is because of the time taken for the hydrogen to build up to critical concentrations by diffusion to the susceptible sites. In contrast to this, the hydrogen levels are so high (around 30 to 40mL/100g) in cellulosic electrode weld metal that there will always be sufficient hydrogen at susceptible sites, and so if cracking is going to occur, it will do so within minutes.

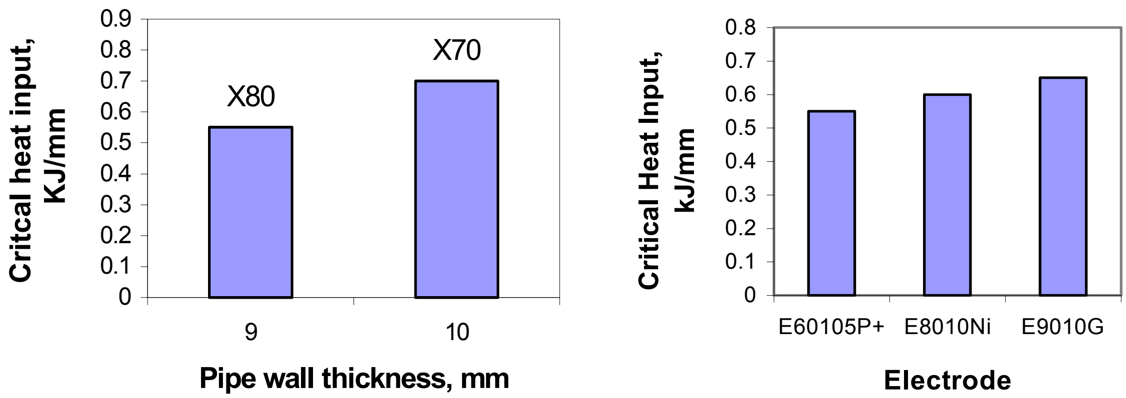
The use of hybrid procedures involving the use of cellulosic electrodes for the root and hot passes, followed by basic coated low hydrogen electrodes for the fill and capping passes may give some reduction in the susceptibility to HACC, however that advantage has to be balanced against the need to be aware of the risk of delayed cracking. The hydrogen content of these hybrid welds will be much higher than welds made with GMAW.

Although the essential variables defined in AS2885.2 are designed to provide a safe operating window, it is known that any significant variation of a combination of these variables could lead to HACC. For this reason the welding process should be supported by a robust quality assurance system to govern the field welding process; such a system is greatly enhanced by involvement of a competently trained welding engineer or supervisor.

It is important to point out that despite these precautions, high strength linepipe, up to grade X80 has been shown to be weldable using conventional welding processes, including manual cellulosic consumables. The resistance of X80 grade pipe to HACC has been evaluated by:

- Welding Institute of Canada (WIC) tests [15],
- Rigid Restraint Cracking (RRC) tests [16],
- Simulated field welding trials using the British Gas test [18], and
- Pipeline construction [19]

The results have demonstrated that Australian produced X80 grade pipe, up to a pipe wall thickness of 9mm, is comparable to X70 in terms of susceptibility to HACC. This is clearly illustrated in Figure 12 where, at maximum stress the critical heat input to generate HACC in 9mm thick X80 pipe was lower than that in 10mm thick X70 grade pipe. This is an important comparison because in terms of pipe design, this represents the typical reduction in wall thickness in moving from X70 to X80. It is also important to highlight the importance of steel alloy design, which can be significantly different depending on the pipe supplier.



(a) (b)

Figure 12. RRC test results on susceptibility to HACC of root pass welds both X70 & X80 grade pipe,
a) Critical heat input required to initiate HACC in both 9mm X80 & 10mm X70 grade pipe using E6010 consumable, and
b) Critical heat input required to initiate HACC in 9mm X80 grade pipe using different strength cellulose consumables.

Weld Metal Strength Matching

Girth weld integrity requires the weld metal to have sufficient strength so that there is a high probability that when a weld containing defects (at the permitted limit) is overloaded in axial tension, the weldment will be strong enough to cause plastic strain in at least one of the adjacent pipes. That is, the weld joint should have sufficient strength, toughness and work hardening characteristics to ensure that fracture, if it was to occur, would proceed by gross section yielding (of the parent pipe) rather than by net section yielding (of the weld).

The controlling factor in determination of girth weld integrity is the permitted level of defects. The Australian Standard AS2885.2 permits a 3-tier approach to assessment of girth weld defect acceptance, which consists of:

- Tier 1 - workmanship base level, similar to that of API 1104,
- Tier 2 - a generalised fitness for purpose (FFP) based level, and
- Tier 3 - which provides for an Engineering Critical Assessment (ECA).

In essence the 3-tier approach permits increased levels of weld defects provided additional mechanical property specifications are satisfied. In other words the level of conservatism is decreased moving from Tier 1 to Tier 3. This approach provides economic benefits to pipeline construction because, provided other factors are equal, this would mean less welds would require rectification. Selection of the appropriate Tier to which girth welds will be sentenced should be agreed upon prior to the finalisation of weld procedures.

It is well known that weld metal yield strength matching with the pipe will provide maximum defect tolerance[20]. Although yield strength matching may be evaluated using a notched tensile test, which is a relatively rapid test, it is conservative and sometimes difficult to interpret [13], particularly where different yielding phenomenon have been found in high strength pipe from different sources. It is however more appropriate to determine weld strength matching rather than weld metal yield strength matching. The former takes into account the factors such as work hardening characteristics; defect limits (particularly depth) and also pipe wall thickness.

Guidelines for determination of defect tolerance require careful assessment using instrumented tests to quantitatively determine critical defect size for particular girth weld configurations. The various test methods available to determine girth weld defect tolerance are presented elsewhere[13]. It is important to say that the aim of these tests is to demonstrate that gross section yielding (GSY), and not net section yielding (NSY), occurs before fracture. There is no universal agreement on the actual minimum acceptable value of strain which must occur in the base metal prior to fracture however there is general agreement that a level of 0.5% is sufficient. This ensures that the yield point of the adjacent pipe is reached and that strain will be distributed along the length of the affected pipeline, and not just the weld metal. This level of strain in a 15m length of pipe represents a displacement of 75mm, which would improve accommodation of displacements in the event of movement such as landslip, erodible valleys or river crossings. It is also important to note that the GSY criteria is not designed to prevent catastrophic failure but to ensure a defined level of defect tolerance or weld performance.

Defect Size and Pipe Wall Thickness

The other important parameters in the determination of defect tolerance include the pipe wall thickness and the defect size, particularly depth. The current standards assume all girth weld defects to be at least one weld pass deep and one weld pass is assumed to be 3mm deep. Whilst this is a reasonable assumption, the defect proportion will increase dramatically as pipe wall thickness decreases.. For example, in 9mm thick pipe the defect represents 30% of the pipe cross section but in 5mm thick pipe, this increases to 60%. This has a significant influence on defect tolerance and is the reason that thick walled pipe can tolerate a lower level of weld metal strength matching compared with thin walled pipe. The influence of pipe wall thickness and critical defect length, at the standard depth of 3mm, is shown in Figure 13.

This relationship between pipe wall thickness and required weld metal strength provides an opportunity for X80 grade pipe to be safely welded using conventional cellulosic consumables. It has been demonstrated that 8.6mm thick X80 grade pipe can be successfully welded using cellulosic consumables and achieve defect tolerance levels significantly greater than that specified in Tier 2 of AS2885 part 2 - 2002 [19].

Mechanical property assessment for Tiers 1 and 2 however differ significantly. Tier 1 specifies the standard battery of weld tests which basically requires that the girth weld demonstrate tensile strength matching using the conventional cross weld tensile test. Tier 2 because of the increased defect allowance requires additional demonstrated weld performance in terms of fracture toughness and weld metal strength. The toughness requirement is 30J minimum individual and 40J minimum average at the minimum design operating temperature and provides assurance against the possibility of brittle fracture. The weld metal strength, as outlined above, provides protection against defect propagation.

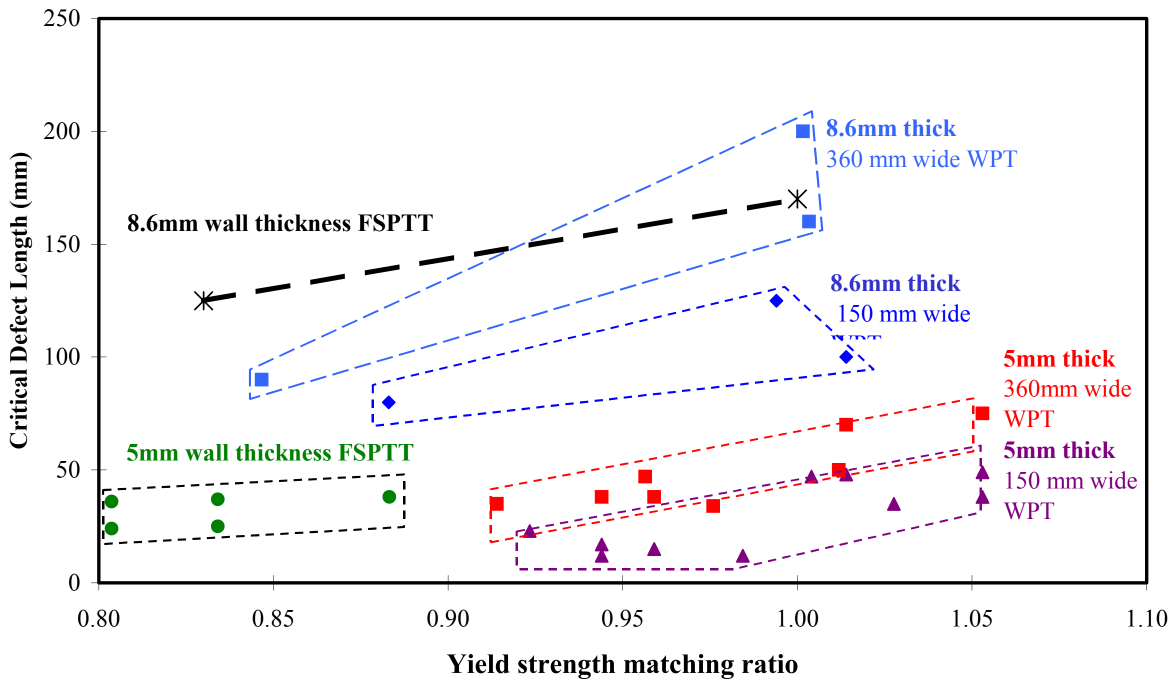


Figure 13. Influence of weld metal yield strength matching ratio, pipe wall thickness and test method on defect tolerance, ie, length of 3mm deep surface defect. WPT = wide plate test; FSPTT = full section pipe tension test (8.6mm wt, 406mm diameter; 5mm wt, 273mm diameter).

Since the introduction of the 3-tier approach it is true to say that the Tier 2 FFP based criteria have not been used. However it should be pointed out that pipelines constructed using X70 grade pipe welded with the cellulosic combination E6010/E8010, which meets Tier 1 Workmanship requirements and has served the industry without any incident, would not meet all current Tier 2 requirements. The results of Australian research have enabled the construction of tables[21], which provide guidance on acceptable weld procedures for X80 grade pipe as a function of wall thickness.

Standards Development

The differences in emphasis in the engineering of Australian pipelines from those constructed in major energy markets elsewhere in the world have led to the development of a full suite of Australian standards for petroleum pipelines.[22] Those standards have been benchmarked against other comparable standards used elsewhere in the world.[23] The benchmarking exercise concluded that they are superior in a number of important respects to the standards to which they were compared. This is attributed to a more flexible standards development process that leads to a more ready adoption of research outcomes and other developments that take place in Australia and other countries.

The Australian suite of standards is especially suitable for the thin walled high strength pipelines that are made using ERW pipe and are the most common type of pipelines that are built in this country.

Summary Comments

1. The norm for Australian pipeline designs is typically 450mm nominal diameter and approximately 10mm wall thickness in grade X70 and potentially X80. The usual design pressure is 15MPa, and the gas is almost always rich which has led to the need for high levels of fracture toughness.
2. The pipe used for these pipelines has been largely produced in Australia from Mo-Nb-Ti steels that give excellent properties with narrow property ranges. An important factor in the alloy design and pipe manufacture philosophy has been the consistent use of the ring expansion test for specifying and controlling pipe yield strength. This has avoided the spurious effects that arise from the use of the flattened bar tensile test.
3. In order to construct long distance pipelines quickly through remote but usually easy pipe-laying terrain, it has become embedded Australian construction practice to use cellulosic electrodes without preheat and high welding speeds with relatively low heat input. This practice has placed special demands upon weldability and upon control of the welding process so as to avoid HACC.
4. Extensive research has defined the critical requirements to avoid HACC and ensure sufficient weld metal strength matching in the welding of X70 and X80 grade pipe. Because of its reduced thickness for a given pressure design, X80 has superior weldability to X70. Both grades can be welded preheat free in thicknesses up to 9mm without HACC, and in wall thicknesses down to 7mm whilst still achieving the level of strength matching necessary for the use of Tier 2 fitness-for-purpose girth weld defect acceptance standards.
5. Whilst strength matching can be achieved using cellulosic electrodes on thin pipe at the upper limit of the production strength range, it cannot be demonstrated using normal cross weld tensile tests, and will likely not be able to be demonstrated using wide plate tests. Full section tensile test methods have been developed and demonstrated for this purpose. Such tests are expensive and are only warranted on large projects. But they are more than justified in order to allow the use of Tier 2 acceptance standards whilst achieving the high construction rates that are afforded by the use of cellulosic electrodes. This is still the fastest and cheapest method of welding pipe less than 500mm nominal diameter.
6. The diverse technologies necessary to construct these pipelines economically whilst providing security of supply and community safety has been adopted and implemented in a set of Australian standards that have attracted notice from the international pipeline community.

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