DEFECT RESISTANCE OF THIN WALLED PIPELINE GIRTHWELDS

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ABSTRACT

The present paper details the development of a wide plate test procedure and method of analysis to provide test data to allow application of fitness for purpose criteria to thin walled (5mm thickness) pipeline girthweld defects. Wide plate tensile specimens produced from flat samples in two pipe steel grades, welded using different consumables and containing artificial defects were tested. The results demonstrated that API-5L-X52 grade material welded with yield strength overmatching consumeable E6010 demonstrated adequate defect tolerance. Higher strength grade API-5L-X70 welded with slightly undermatching consumables E6010 and E6010/E8010 demonstrated less defect tolerance, a result that was attributed to weld metal and base plate mechanical properties. Critical defect lengths obtained increased with increasing test piece width and increasing weld reinforcement.

KEYWORDS: pipeline girth weld, defect acceptance limits, fitness for purpose, wide plate test

INTRODUCTION

The rate of pipeline construction is largely dependent upon the rate at which girth welds can be made and especially upon the cycle time for the completion of the root bead connection (Wilson, 1984). To this end it is important to ensure that weld defects failing workmanship standards are not rectified unnecessarily. Modern radiographic techniques have however led directly to discovery and rejection of increasing numbers of imperfections, especially in welds made with the traditional cellulosic stovepipe welding method.

Fortunately, there has been a concomitant development of the means of determining the engineering significance of such defects using fracture mechanics methods (Anon. BSI, 1991) which have been included in a number of industry standards (Anon., API, 1988; Anon. BSI, 1984; Anon. CAN/CSA, 1986; Anon. SAA, 1987). The driving force for these developments has been the cost of unnecessarily rectifying defects and also to avoid the potential introduction of more harmful and/or less readily detectable flaws. However, despite the improvement in radiographic techniques the more significant planar defects are not easily detected. More importantly, when planar defects are detected the most critical parameter necessary for sentencing (ie, defect depth) is not easily quantified. This situation is met by assuming that all planar defects are one weld pass deep, a figure generally taken to be 3mm. Girth welds in 5mm thick line pipe would contain a minimum of three weld beads, and it is safe to assume that the maximum depth of any one bead would be less than 50% of the wall thickness.

European Pipeline Research Group Guidelines (EPRG): Relevance to Australian Scene.

The EPRG carried out a large testing programme using the wide plate test (Hopkins, 1993, Denys, TBP) which in combination with full size pipe tests (Hopkins, 1993) gave an extensive database of failure conditions for real and artificial defects. The EPRG Guidelines developed from these results are based upon an underlying philosophy of ensuring plastic collapse by prescribing a Charpy energy of 40J minimum average / 30J minimum individual at the relevant temperature for thicknesses up to 13 mm (Anon. 1994).

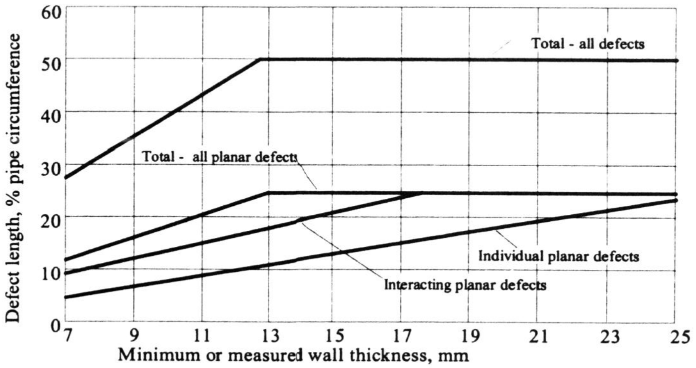


Fig. 1: Girth weld defect limits for EPRG Tier 3 (after [15]).

Unfortunately, the EPRG guidelines do not extend below a thickness of 7 mm (Figure 1, (Anon., 1994)) and therefore do not address thin walled pipe. In order to address this issue, a wide plate test programme has been undertaken by the Welding Technology Institute of Australia / Australian Pipelines Industry Association (WTIA/APIA) Research Panel 7 and the Cooperative Research Centre (CRC) for Materials Welding and Joining, to investigate extension of the plastic collapse provisions of the EPRG guidelines down to 5 mm wall thickness.

The test programme was simplified because the fracture mode in the thin walled material has been shown to be plastic collapse (Hopkins & Denys, 1993), so that CTOD testing is not required, and since plastic collapse is insensitive to notch acuity the artificial defects do not need to be fatigue sharpened.

MATERIALS AND EXPERIMENTAL PROCEDURE.

Materials

Wide plate test pieces were prepared from stovepipe welds produced in flat strip of grades X52 and X70 in the as-rolled and levelled condition. Chemical analyses are reported in Table 1.

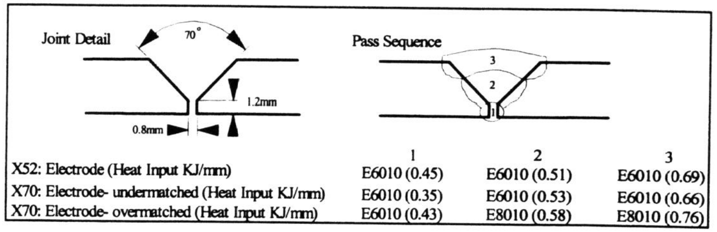
Welding details are given in Figure 2. The X52 material was welded throughout with E6010 consumables with the expectation of an overmatched weld. The X70 material was firstly welded throughout with E6010 (undermatched) and secondly with E6010 in the root bead and E8010 for the remainder (expected to be overmatched). Weld tensile properties were determined from notched tensile tests using the procedure defined by Denys, 1994. Substandard size Charpy tests (5 X 10 mm) were performed in the temperature range -50 to +25 °C.

Table 1: Chemical Composition of Strip Material & Developed Welds (Capping Pass Only)

	C	P	Mn	Si	S	Ni	Al	Nb	Ti	V	Ca
X52 Strip	0.09	0.015	0.65	0.14	0.003	0.031	0.043	0.027	0.023	0.006	0.0032
X70 Strip	0.09	0.015	1.51	0.30	0.002	0.024	0.023	0.040	0.012	0.059	0.0008
E6010 in X52	0.125	0.014	0.61	0.18	0.013	0.023	0.005	0.005	0.017	0.003	<.0005
E6010 in X70	0.135	0.013	0.85	0.21	0.011	0.020	0.006	0.009	0.016	0.018	<.0005
E8010 in X70	0.115	0.014	1.12	0.20	0.015	0.15	0.004	0.005	0.015	0.018	<.0005

Wide Plate Test Procedure.

The gross section yielding (GSY) technique devised by Denys, 1984, was adopted as the method of evaluation of defect acceptance. This technique is based on the concept that if the parent plate (gross section) containing a weld with a defect yields before failure occurs at the defect or before maximum load is achieved, then the defect can be safely left in the structure. It remains then for the acceptable defect length to be determined. The EPRG limit for an individual planar defect extrapolated down to 5 mm is 2.9% of pipe circumference (Anon., 1994). From pipe diameters and wall thicknesses specified in API SPEC 5L (4.8mm thick, 447.4mm dia.; 5.2mm thick, 396mm dia.) this is determined to be 38mm maximum.



	1	2	3
X52: Electrode (Heat Input KJ/mm)	E6010 (0.45)	E6010 (0.51)	E6010 (0.69)
X70: Electrode- undermatched (Heat Input KJ/mm)	E6010 (0.35)	E6010 (0.53)	E6010 (0.66)
X70: Electrode- overmatched (Heat Input KJ/mm)	E6010 (0.43)	E8010 (0.58)	E8010 (0.76)

Figure 2: Welding procedure.

A schematic diagram of the test pieces employed is given in Figure 3. To provide additional conservatism, the majority of 150mm wide parallel length test pieces had the weld reinforcement removed from both the root and capping passes. An assessment of the influence of weld reinforcement was also carried out on a limited number of tests. Parent plate wide plate tests were also carried out for comparison with the different strength matching effects caused by the various weld consumables, particularly in the case of the X70 grade strip. Artificial defects were located in the centre of the weld and test piece width on the root pass side only as experience has shown the most probable defect to be a root pass flaw. A schematic diagram of defect position is shown in Figure 3. Defect profile chosen was semielliptical with a maximum nominal depth of 3 mm, refer also Figure 3. This profile offers a degree of conservatism in defect area when compared to the average defect depth of 1.5 mm reported by Hopkins, 1993: Hopkins & Denys, 1994), while maintaining a connection with the well accepted maximum weld pass depth of 3 mm. Defect lengths were chosen to span the defect length required by EPRG limits extrapolated down to 5 mm wall thickness. Lengths employed were 25, 38 & 50mm for X52 grade material and 15, 25, 38 & 50mm in the case of X70 grade material.

Table 2: Mechanical Properties of Strip & Welds (Longitudinal)

Strip tensiles Strip Grade/Weld	0.5% Total Elongation Yield Stress MPa	Tensile Strength MPa	Total Elongation %	Yield/Tensile Ratio %
X52 actual	376	469	42	80
specified min. (trans.)	358	455	22.5	
X70 actual	539	601	33	90
specified min. (trans.)	482	565	18.5	
Notched Tensiles in Weld (Denys, 1994(1))				
E6010 in X52	396	510		78
E6010 in X70	509	606		84
E6010/E8010 in X70	517	605		85

A series of 360mm wide parallel length test pieces containing welds with reinforcement intact were also prepared and tested. Defect lengths were 38 and 50mm in X52 welded with E6010 and 25 and 38mm in X70 weldments (both E6010 and E6010/E8010 consumables).

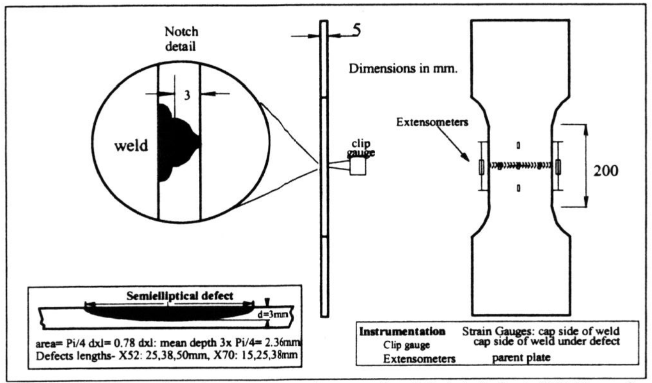


Figure 3: Schematic diagram of wide plate test piece and artificial defect. Widths of parallel length 150 or 360mm, for gauge lengths of 200 and 400mm respectively.

The artificial defects were produced by electro-discharge machining to ensure accurate location and size. Defect width was 0.6mm. As toughness is ensured if the minimum Charpy impact property is achieved, failure is expected to occur by plastic collapse so that notch acuity was not an issue in terms of the method of machining employed.

Test instrumentation for 150mm wide parallel length tests is shown in Figure 3. Tests were performed at room temperature (24°C). Simulation of the high level of constraint expected in a real girth weld was checked by ensuring that the test piece gauge length remained parallel up to the maximum gross stress (Denys, 1982). 360mm wide test pieces were monitored with extensometers and clip gauge, but strain distributions were measured by Moire fringe method.

RESULTS AND DISCUSSION.

Material Properties.

Chemical composition of strip materials and weld capping passes are given in Table 1. The significant difference in deposited weld composition was the increase in manganese level of E6010 used in the X70 strip and the presence of nickel in the higher strength E8010 deposit.

Mechanical properties (Table 2), indicate that weld metal yield strength overmatching was achieved with E6010 in X52. However both E6010 and E8010 deposits in X70 grade strip, while matching parent metal tensile strength, were undermatched in yield strength by 30 and 22 MPa respectively. Charpy test results (Table 3), when adjusted pro rata to a standard 10 X 10 mm test piece, satisfy the requirements of 30J minimum individual and 40J minimum average requirement in Australian Standard, AS2885.2-1995 Tier 2. The results also indicate that at the wide plate test temperatures (+24°C) the welds would be ductile in terms of the EPRG requirements.

Wide Plate Test Behaviour.

Wide plate test records representing the two main failure modes are given in Figures 4a & b. The combined plots of gross section stress (σ_N) and crack mouth opening displacement (CMOD) of the defect as a function of elongation clearly demonstrate how the strain is distributed between the parent plate and the weld containing the defect. In Figure 4a, which represents failure by net section yielding (NSY), the CMOD increases linearly up to the maximum gross stress indicating that the strain is

Table 3: Charpy toughness test results.

Steel Grade	Weld Metal	Test Temp. °C	Substandard test		Energy, corrected to 10mm, J			Fibrosity, %	
			Thickness mm	Individual Energy, J	Individual	Min.	Mean	Individual	Mean
X52	**E6010**	**0**	5.00, 5.33, 5.12	47, 58, 46	94, 108, 90	**90**	**97**	100, 100, 100	100
		-25	5.04, 5.23, 5.07	27, 50, 28	54, 96, 56	**54**	**69**	60, 90, 55	68
		-50	5.08, 5.22, 5.22	14, 17, 18	28, 32, 34	**28**	**31**	25, 30, 30	28
X70	**E6010**	**25**	5.29, 5.34, 5.33	42, 43, 42	80, 80, 78	**78**	**79**	98, 95, 100	98
		0	5.36, 5.27, 5.39	40, 26, 43	74, 50, 80	**50**	**68**	85, 65, 90	80
		-25	5.34, 5.55, 5.28	22, 17, 20	42, 30, 38	**30**	**37**	55, 25, 35	38
X70	**E6010/E8010**	**25**	5.49, 5.60, 5.59	39, 52, 53	72, 92, 94	**72**	**86**	95, 100, 100	98
		0	5.51, 5.59, 5.69	26, 36, 33	48, 64, 58	**48**	**57**	70, 60, 50	60
		-25	5.65, 5.69, 5.69	29, 19, 10	52, 34, 18	**18**	**35**	45, 35, 25	35

confined to the weld containing the defect. Failure by this mechanism would indicate that defect dimensions exceed that deemed fit for purpose.

The example of gross section yielding (GSY) in Figure 4b shows the gross stress initially increasing linearly followed by yield behaviour, ie strain at constant stress. The CMOD value after some initial increase, plateaus out after parent plate yielding. In this particular case where GSY occurs, the gross stress in the weld metal exceeds the yield strength of the parent strip, $\sigma_N >= \sigma_y$, due to work hardening. Such behaviour, which readily occurs with overmatched weld metal yield strength, transfers strain to the parent strip and thus protects the defect.

An alternative method of test data assessment is to plot σ_N versus defect area, as shown in Figures 5a to c. Theoretically with increasing defect area the gross stress to failure should decrease linearly, as shown by the line extending down to gross cross sectional defect area/zero stress. However, due to a difference between parent and weld material properties and because of defect characteristics the actual value is less than the linear relationship. Specifically, deviations from the simple reduction of area model increases as the yield stress/tensile stress (YS/TS) ratio and the level of weld metal strength undermatching increase. When a line of best fit is drawn through actual test results for particular strip - weld combinations, an experimental gross section stress - defect area plot is obtained. The intersection of this line with the actual parent strip yield strength defines the critical defect area, which can be converted to a critical defect length.

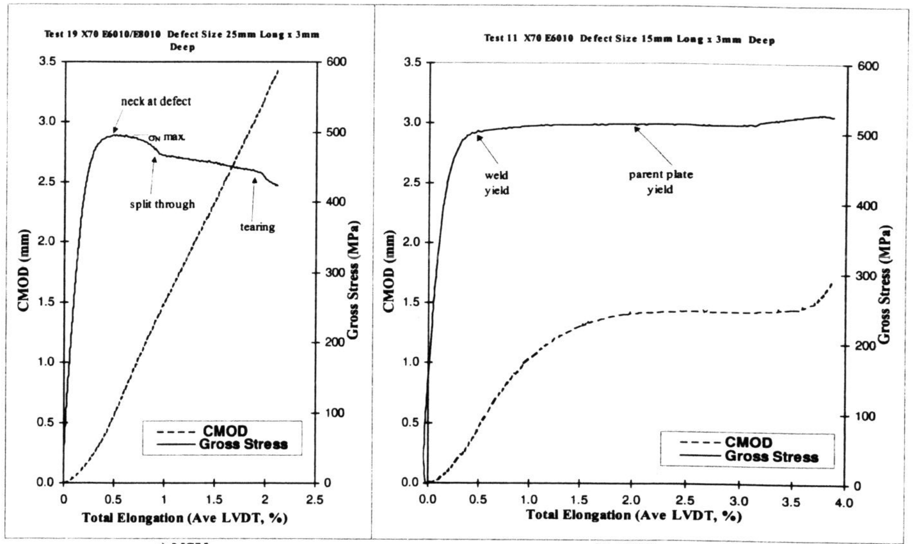
Therefore, by inspection of test records and examination of σ_N & σ_y relationships, achievement of the desirable GSY failure mode can be detected. In addition the weld must be protected adequately from excessive strain. The EPRG found that if a minimum level of parent metal strain of >= 0.5 %, was attained, then the weld was protected from excessive strain (Hopkins & Denys, 1993). The critical results of the wide plate test programme are summarised in Table 4 together with evaluation of failure mode based on the above assumptions. It is interesting to note that the minimum strain requirement in parent plate of 0.5%, is consistent with the observation of GSY determined by the $\sigma_N >= \sigma_y$ condition. The validity requirement that the test piece gauge length remain parallel was met where GSY was achieved.

The 150mm parallel length test results demonstrated that in the case of X52 grade material welded throughout with E6010 consumable, in the absence of any significant weld reinforcement, the critical length of defect (3mm deep) was 38 mm (Figure 5a). In the presence of weld reinforcement, (estimated to increase the net section area of weld by approximately 13%), the critical defect length increased to 49 mm. The 360mm wide parallel length test results extended this limit by 50% to 75mm. These results indicate that X52 grade strip welded throughout with a weld consumable which meets the specified minimum mechanical properties (as previously outlined) complies with defect acceptance levels outlined by the EPRG (Tier 3, planar defects) down to 5 mm wall thickness.

For both combinations assessed in X70 grade material compliance with EPRG Tier 3 was not observed using 150mm wide parallel length test pieces. No effective difference in critical defect length was detected between the E6010 and E6010/E8010 welds. The recorded critical defect length, in the absence of weld reinforcement, was 12 mm (Figures 5b & c), significantly less than the 38 mm estimated by extension of the EPRG guidelines down to 5 mm wall thickness. The influence of an increase in weld net sectional area afforded by weld reinforcement again provided additional defect tolerance but failed to meet the estimated minimum required for 5 mm thick line pipe. The 360mm wide parallel length tests however extended the limits to 42mm (150% increase compared to 150mm wide parallel length test piece) for E6010 and 45mm (200% increase) for E6010/E8010 welds, results which do validate these consumables applied to X70. However the parent metal strain levels (0.32% and <0.55%) indicate the validation is marginal.

The recorded performance of the higher strength X70 grade material may potentially be attributed to:

- limitations in the overly conservative test method and/or
- material properties characteristic of welded high strength line pipe.



a) NSY b) GSY

Figure 4: Test records showing fracture modes.

It is apparent that a limited test piece width (150 mm) does not provide sufficient constraint at maximum defect length in the absence of weld reinforcement and with a surface breaking artificial defect. The 360 mm wide test is just adequate in these circumstances. However if a more realistic artificial defect depth of 2.5mm were used then significantly higher strains and GSY would have occurred (Lefevre 1996) in the 360mm wide tests for the plate/weld metal combinations utilised. It should be noted that the X70 parent plate material (yield stress 517-539 MPa) was not selected from the upper end of the yield stress range which can be specified minimum yield stress (482MPA) + 100/120.MPa. Further testing of X70 from the upper end of the yield stress range is indicated using 360mm wide test piece.

Material properties known to influence weld metal defect tolerance are:

- weld metal strength matching, and
- strain hardening capacity of both weld and base metals, (ie, YS/TS ratio).

The issue of YS/TS ratio is paramount particularly when the weld metal yield strength does not overmatch the base plate. Moreover, it has been shown (Hopkins & Denys, 1993) that the critical

YS/TS ratio for NSY or GSY decreases with pipe wall thickness and also increasing flaw dimensions.

To investigate this aspect, additional 150mm wide wide plate tests were carried out with the defect located entirely in the parent strip. This eliminated the effect of yield strength differences between the weld metal and base strip. The results also given in Table 4 show a further decreased defect tolerance level in both X52 and X70 grade strip. As yield strength surrounding the defect is uniform, the observed decrease in defect tolerance compared to weld metal is therefore assumed to be attributed to the relatively low work hardening capacity of the strip compared to weld metal as defined by the YS/TS ratio.

Therefore, from the Australian Pipeline Industry perspective where pipe wall thickness tends to be "thin" and with a trend towards increasing pipe strength, the need to assess weld defect criteria for higher strength grades is essential. Further work is underway to investigate defect acceptance levels in high strength pipeline girth welds.

Table 4: Wide plate test results.

Thickness, t: X52 strip, 4.98mm X70 strip, 5.15mm			Test piece width	reinforcement		Defect dimensions			Maximum gross sect. stress σ_N	parent metal strain e_P	Failure mode	
				height h	prop. of strip thick	length l	depth d	area A			based on parent metal strain: >=0.5%:GSY <0.5%:NSY	based on Moire fringes
Test	Combination		mm	mm	%	mm	mm	mm^2	MPa	%		
1	X52-E6010 "over-matched"	with reinf.	150	1.74	35	0	0.0	0	464	>0.85, >0.89	GSY	
2			150	1.19	24	50	3.0	118	371	0.41, 0.28	NSY	
3		with-out reinf.	150	0.49	10	0	0.0	0	456	>3.6, >0.17	GSY	
4			150	0.58	12	25	2.7	53	429	>1.5, >0.61	GSY	
5			150	0.41	8	38	2.7	81	386	>1.12, >0.58	GSY	
6			150	0.38	8	50	3.0	119	354	0.29, 0.28	NSY	
7	X52 parent pl.		150	0	0	38	3.0	90	348	0.24 0.24	NSY	
A	X52-E6010 "over-match"	with reinf.	360	1.6	33	38	3.0	90	430	3.76	GSY	GSY
B			360	1.5	31	50	3.0	118	400	2.42	GSY	GSY
8	X70-E6010 "under-matched"	with reinf.	150	1.62	31	0	0.0	0	592	>0.86, >0.71	GSY	
9			150	1.09	21	25	3.0	59	512	0.42, 0.39	NSY	
10		with-out reinf.	150	0.47	9	0	0.0	0	592	>2.7, >1.18	GSY	
11			150	0.43	8	15	3.1	36	527	3.85, 3.48	GSY	
12			150	0.38	7	25	2.7	53	505	0.42, 0.36	NSY	
13			150	0.28	5	38	2.7	81	448	0.34, >0.32	NSY	
14	X70 parent pl.		150	0	0	15	2.9	34	506	0.53, 0.45	NSY	
C	X70-E6010 "under-match"	with reinf.	360	1.7	33	25	3.0	59	554	2.74	GSY	GSY
D			360	1.6	32	38	3.0	90	540	0.32	NSY	onset GSY
15	X70-E6010 /8010	with reinf.	150	1.33	26	0	0.0	0	592	>0.97, >0.70	GSY	
16			150	1.5	29	25	3.0	59	506	0.45, 0.34	NSY	
17	"over-matched"	without reinf.	150	0.21	4	0	0.0	0	587	>5.0, >1.93	GSY	
18			150	0.34	7	15	3.0	35	534	>3.6, >2.49	GSY	
19			150	0.32	6	25	2.7	53	496	0.35, 0.32	NSY	
20			150	0.15	3	25	3.0	59	486	0.38, 0.38	NSY	
21			150	0.37	7	38	2.7	81	494	0.38, 0.30	NSY	
E	X70-E6010/E8010 "over-match"	with reinf.	360	1.6	32	25	3.0	59	566	3.00	GSY	GSY
F			360	1.7	33	38	3.0	90	529	<0.55	GSY	GSY

Maximum gross (strip) section stress σ_N=Max. force attained/150t or 360t.

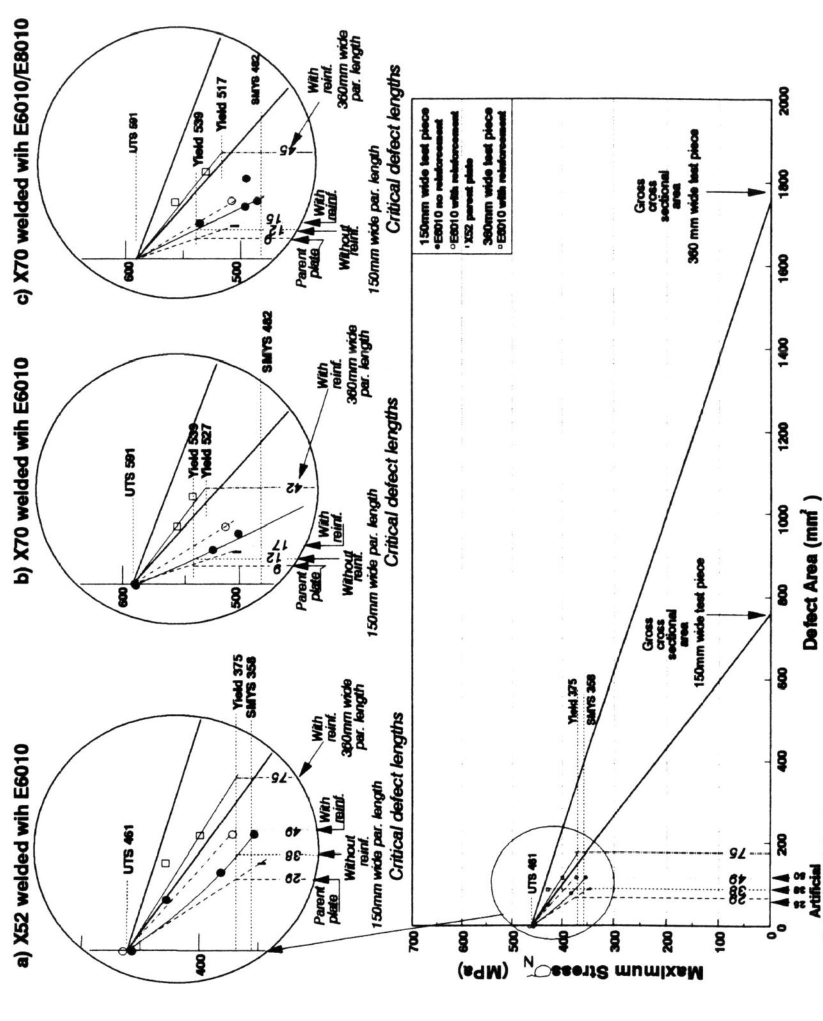


Fig. 5: Wide plate test results. At bottom, Maximum Stress versus Defect Area plot for X52 wide plate tests. At top, a), magnified detail of this plot showing of critical defect area determination for X52 (welded with E6010). b) and c) are magnified detail of similar Stress versus Area plots for X70 (E6010) and X70 (E6010/E8010) respectively.

Modelling of Experimental Results - 150mm wide parallel length tests.

A simple interpretation of the effect of defects in welds is the reduction of area model (Denys, 1994(2)), described by:

$$\sigma_N=\sigma_{UTS}(1-A/A_N) \qquad (1)$$

where A=defect area and A_N= gross (parent plate) section. This equation describes the straight line drawn from tensile strength-zero defect area to zero gross stress-gross section defect area points in Figures 5a to c. It is evident that this model is not conservative as the predicted maximum σ_N is not achieved with real defects due to material characteristics and stress concentration effects. If a correction factor α is incorporated to account for the experimental values, then Equation 1 becomes:

$$\sigma_N=\sigma_{UTS}\alpha(1-A/A_N)=\sigma_{UTS}\alpha(1-\pi ld/4tw) \qquad (2)$$

Table 5: Reduction of Area Model Correction Factors from Test Results

Strip Grade	Weld Metal	Reinforcement	mm	Correction Factor α
X52	E6010	nominally without	0.4	0.924
		with	1.15	0.962
X70	E6010	nominally without	0.4	0.947
		with	1.09	0.962
X70	E8010	nominally without	0.35	0.947
		with	1.5	0.956

The value of α obtained when Equation 2 is applied to the critical defect lengths in 150mm wide parallel length test pieces for X52 and X70 without reinforcement, are 0.924 and 0.947 respectively, refer Table 5.

If σ_y is substituted for σ_N and Equation 2 rearranged to allow the prediction of critical defect length Equation 3 is obtained:

$$l=(4tw/\pi d)x(1-\sigma_y/\alpha\sigma_{UTS}) \qquad (3)$$

where σ_y and σ_{UTS} are the strip yield and tensile strengths respectively.

To understand the extent of conservatism in prediction, the effect of residual reinforcement in tests hitherto referred to as without reinforcement, must be accounted for. This can be done by plotting α against measured reinforcement as shown in Figure 6. While this data is limited, it suggests that, when extrapolated linearly to zero reinforcement conservative values for α with no reinforcement, ie 0.9 for X52 and 0.94 for X70 can be obtained. When substituted in equation 3, these values of α predict critical defect lengths in thin walled wide plate tests with reinforcement completely removed, of 30 mm for X52 and 10 mm for X70 respectively, refer Table 6.

Table 6: Comparison of Actual & Calculated Critical Defect Lengths (Eq. 3, see text)

Strip Grade	Actual Critical Defect Lengths (mm)		Calculated Critical Defect Lengths		
	nom without reinf.	with reinf.	α	without reinf. semielliptical defect	no reinf., average defect depth 1.5 mm
X52	38	49	0.9	30	47
X70	12	15/17	0.94	10	15

If now the conservatism of the semielliptical defect used in this programme is removed by replacing π with 2 in Equation 3 to simulate the 1.5 mm average defect depth observed by Hopkins, 1992, then the predicted critical defect lengths are 47 mm and 15 mm for X52 and X70 respectively, again refer Table 6. As these results are similar to the critical defect lengths obtained from the tests with reinforcement (X52, 49 mm; X70 15-17 mm) it is apparent that testing a weld with reinforcement and a 3mm deep semielliptical defect is equivalent to testing a weld without reinforcement with a defect of average depth 1.5 mm. Thus the conservatism introduced by using a semielliptical defect without reinforcement is similar to using the more realistic average defect depth of 1.5 mm in a weld with reinforcement intact.

Again it is stated that the data leading to this conclusion is limited by the fact that only three tests were performed with reinforcement intact. However it does emphasise the conservatism of the test programme, and suggests that further work investigating shallower defects would be fruitful. Further modelling is in progress in an effort to understand the effects of weld metal strength matching on the failure of girth welds in high strength thin walled line pipe.

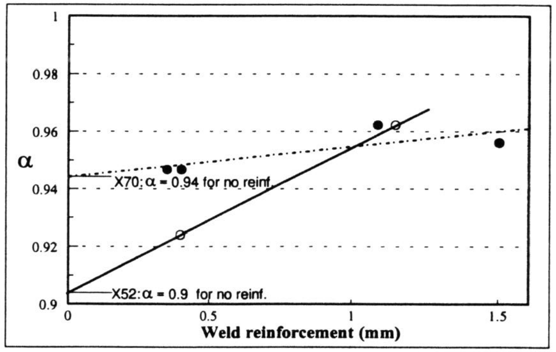


Figure 6: Effect of weld reinforcement on correction factor α for reduction of area model.

CONCLUSIONS

On the basis of the results obtained from the wide plate tensile test assessment of defect acceptance levels in thin walled pipeline girth welds, the following conclusions are drawn:

1. API-5L-X52 grade pipe welded throughout using E6010 (E4110) consumables provides both yield and tensile strength overmatching. E8010 (E5510) provides marginal tensile strength matching in API-5L-X70 grade line pipe.
2. Charpy impact properties of E6010 (E4110) and E8010 (E5510) consumables quite satisfactorily meet the minimum requirements to ensure ductile fracture
3. Critical defect length determined using the wide plate test increased with increasing test piece width and weld reinforcement.

4. API-5L-X52 welded throughout with E6010 consumables has validated extension of fitness for purpose defect acceptance levels outlined in AS2885.2-1995 (and the EPRG guidelines) extrapolated down to 5 mm wall thickness.
5. API-5L-X70 welded with either E6010 or E8010 consumables did not satisfy requirements of AS2885.2-1995, Tier 2, defect limits extrapolated down to 5 mm wall thickness. This may be attributed to limitations in the overly conservative test method and/or material property characteristics of welded high strength line pipe.
6. X70 with yield stress from the upper end of the distribution should also be tested in order to investigate the effect worst case weld metal strength matching.

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