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EVALUATING MECHANICAL PROPERTIES OF HYBRID LASER ARC GIRTH WELDS

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ABSTRACT

This paper presents the challenges and results associated with mechanical testing of overmatched X80 and X100 pipeline steel girth welds that were produced by Hybrid Laser Arc Welding (HLAW). The weld profile produced by this process is characterized as having a broad weld cap and a narrow leg, which traverses the through thickness direction.

The development and testing of the HLAW process was conducted on NPS36 pipes of 10.4 mm and 14.3 mm thickness, respectively. The welds were deposited in the 5G welding position with all parameters and laser visual inspection data being collected for each weld pass. Subsequent sample extraction and testing of the hybrid laser arc welds were achieved by standard test practices for girth welds and modifications of these practices, where the latter was required to facilitate testing of the narrow HLAW geometry.

Charpy results indicate that the fracture transition temperature, with the notch in either the weld metal or the heat-affected zone (HAZ), is higher at the 3 and 9 o'clock positions when compared to 9 and 12 o'clock positions. The likelihood of crack deviation influencing the results due to the non-conventional weld geometry needs to be examined in a further study. For crack tip opening displacement (CTOD) testing, shorter fatigue crack lengths were employed to reduce the possibility of fatigue crack deviation. The results show that this method does not influence the validity of the test outcomes.

INTRODUCTION

The cost of welding is a major component of the overall construction expenditure and industry continues to seek future generation pipeline welding technologies to improve productivity and to enable significant cost savings. HLAW is a promising technology that is destined to increase the efficiency and productivity of welded fabrications. By incorporating automation and integrating an automated inspection system, HLAW is expected to produce high quality welds at higher production rates compared to even the most advanced pipeline welding systems that are in use today. Continued technological advancements are considered essential requirements for the construction of pipelines that transport oil and gas from remote locations.

For this body of work, a HLAW system has been designed, assembled, and tested on X80 and X100 NPS36 pipes, having 10.4 mm and 14.3 mm wall thickness, respectively. HLAW procedures were developed and optimized for each wall thickness aimed at depositing high speed root passes in the hybrid laser keyhole mode, called the "hybrid", at welding speeds approaching 2500 mm/min. Subsequent high-speed fill and cap passes were then deposited with laser assisted Gas Metal Arc Welding (GMAW). All welds were deposited in the 5G welding position (pipe is horizontally fixed) using a Thyssen NiMo80 electrode.

Welded specimens were subsequently extracted and were tested using all weld metal (AWM) tension tests, Charpy V-notch impact tests and quasi-static (QS) CTOD tests. This paper outlines the specimen extraction methods, test procedure development and the results obtained from the work completed at this stage.

TEST PROCEDURE DETERMINATION

In North America, the standard test procedures for pipeline girth weld testing are API 1104 [1] and CSA Z662 [2]. In this work, the standard test API 1104 was adopted giving consideration to the HLAW geometry (Fig. 1). It can be observed that the GMAW portion of the HLAW weld is positioned on top of the hybrid pass, which combined, produces a non-typical weld profile.

It can also be seen that the X100 pipe used in this study has three additional laser assisted GMAW deposits, compared to one additional deposit for the X80 pipe. The reason for this difference is attributed to the larger wall of the X100 pipe. A general characteristic feature of a HLAW weld is however that the root pass in the keyhole mode is approximately 1 to 2 mm wide.

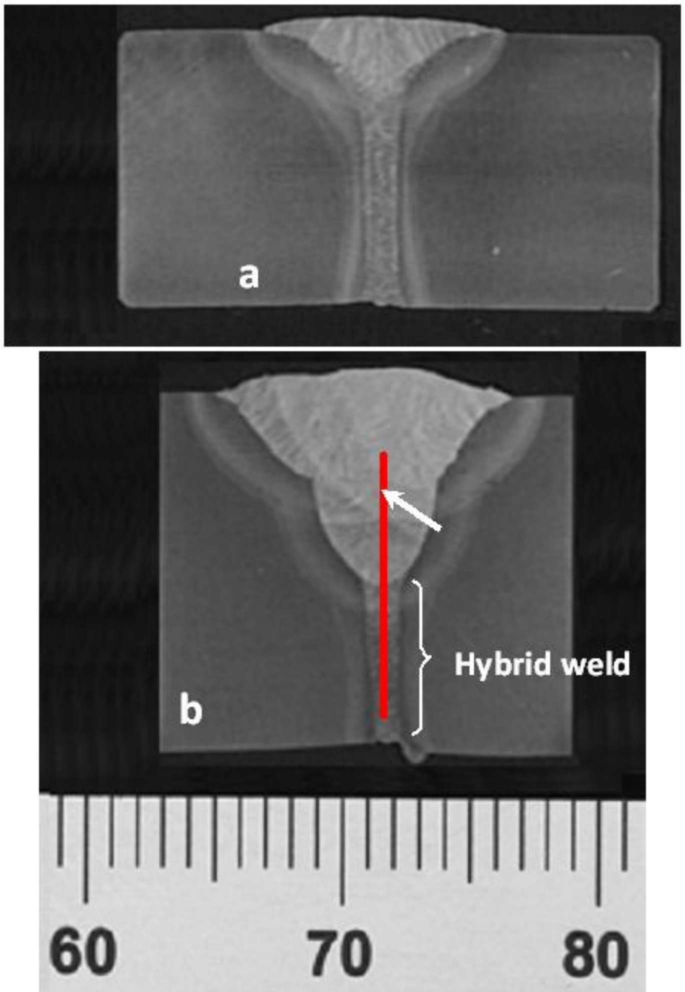

Figure 1: HLAW weld macros for (a) X80 and (b) X100 pipe.

In Fig. 1b, the red vertical line indicates the all weld metal strip specimen gauge length with respect to the pipe wall, and the arrow indicates the location of the Hounsfield tensile specimens.

SPECIMEN EXTRACTION PROCEDURES

Tension Specimens

The focus was to evaluate/modify currently adopted practices for extracting and testing AWM specimens from the girth weld. The primary challenge in this focus was the feasibility of including the narrow hybrid pass.

Two AWM specimen types were considered to be viable test configurations. These were; (a) round bar and (b) strip specimens. Both of these AWM specimens are currently non-standard API 1104 test methods, although the round bar type has previously been adopted to determine tensile properties of GMAW girth welds [3].

In that study, strip specimen geometry was evaluated for determining the tensile properties of a GMAW cross section and it was then compared to the round bar [3]. It should also be noted that the strip specimen usually does not meet the gauge section dimensions of ASTM E8 guidelines. Fig. 2 shows the dimensions of the strip specimens adopted for the HLAW. The AWM strip specimen was profiled by electric discharge machining (EDM) and the test gauge length was cleaned by polishing with emery paper to remove any affected layer of material from the EDM process. For the X80 pipe, the gauge section was 7.4 mm (pipe wall direction) x 0.8 mm (hybrid weld width) and for X100 pipe it was 10.9 mm x 0.8mm to only sample weld metal. The gauge location marked by the red line with respect to pipe wall in Fig. 1b.

The narrow constraints of the hybrid weld did not permit the extraction of round bar specimens, and instead, a round bar was extracted from the fill and cap passes deposited with laser assisted GMAW. The round bar was extracted using the EDM process. It was then possible to machine a 3 mm diameter Hounsfield specimen (Fig. 3) centered at the cross hair (marked by the white arrow) in Fig. 1b. This was however only feasible for the X100 weld due to the single cap pass of the X80.

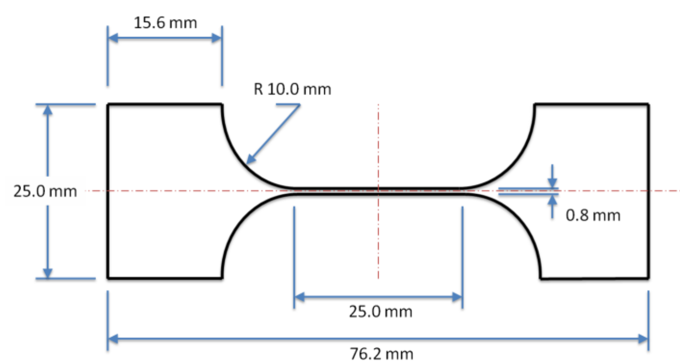

Figure 2: CAD drawing showing the Strip Specimen Profile Dimensions (inch).

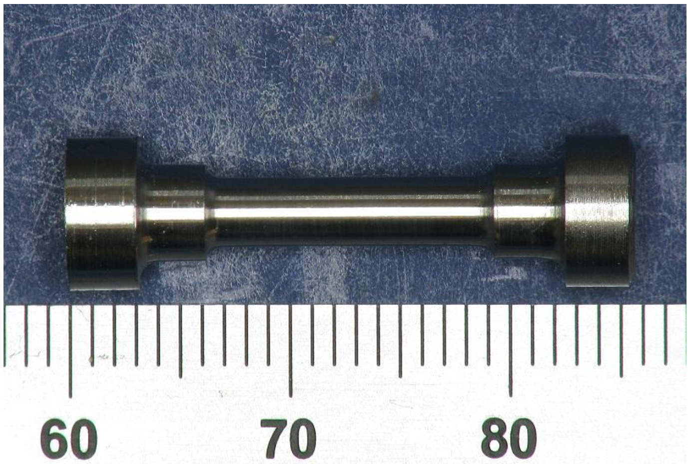

Figure 3: Hounsfield specimen

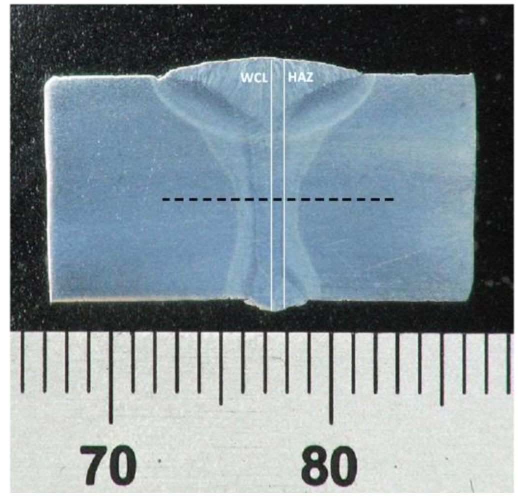

Figure 4: The white lines represent typical placement of the through thickness notch for WCL and HAZ locations. The broken line is the mid-thickness plane where selected specimens were sectioned for metallography.

Charpy Specimens

The standard Charpy notch has a root radius of 0.25 mm (ASTM E23), which is considerable when compared with the dimensions of the hybrid weld width and the entire HAZ shown in Fig. 1. Accurate notch placement is therefore crucial when attempting to sample the weld or HAZ.

The Charpy V-notch impact test specimens were extracted from X80 grade, where the objective was to assess the four quarters of the circumferential HLAW pipe. These four quarters represented the 12, 3, 6 and 9 o'clock positions. The thickness of the X80 pipe materials was 10.4 mm, which resulted in 80% sub-sized Charpy specimens.

Due to misalignment in the sample pipe welds (Hi-Lo), it was necessary to extract specimens from two pipe sections that were welded under identical conditions. Specimens from the 12 and 3 o'clock positions were extracted from pipe 507, and specimens from the 6 and 9 o'clock positions were extracted from pipe 503. For the 12 o'clock position, the specimens were extracted from 11:30 to 1:30 and similarly for the other clock positions. Consideration was also given to indications (flaws) from ultrasound testing (UT), which resulted in the exclusion of certain regions.

Guidelines from API 1104 (Section A.3.2.2.1) were mostly adopted during the extraction and machining of these clock positions. The V-notch was placed in the straight HAZ of the hybrid portion and therefore deviated from the notch location suggested in the guidelines of API 1104. The weld centerline (WCL) notch location was placed according to the API 1104 guidelines. Fig. 4 shows the typical notch locations for the WCL and HAZ specimens, noting that the notch locations for both the HAZ and the WCL are separated by approximately 1 mm. The placement of the notch therefore required considerable care because the narrow profile of the HLA weld increased the level of accuracy required. The notch was placed in a direction that was opposite to the direction of welding.

In order to maximize sampling of the HAZ, the HAZ Charpy coupons were extracted as close as possible to the ID surface. A line was then scribed centered along the HAZ of the laser part of the weld to serve as the location for notch-placement. The subsequent notch would then traverse through the three regions, namely the HAZ of the HLA weld, the HAZ of the GMAW and also a section of the weld cap (see Fig. 4).

CTOD Specimens

The standard CTOD test procedures require that the fatigue crack growth from a machined notch be extended sufficiently, (i.e. a minimum of 1.3 mm). The primary reason for this may originate from the first CTOD test standard (BS 5762: clause 5.2) where a machined notch with a 60° tip was specified. More recently, ASTM E1820-06; clause 7.4.5.1, allows for shorter fatigue cracks from a narrow machined notch. At BMT Fleet Technology Ltd, the narrow notch profile has been used successfully with an integral knife edge machined by EDM. The advantage of a shorter fatigue crack in testing the HLA weld is that any crack deviation during the fatigue, limits the movement of the tip of the fatigue crack from the "optimized" EDM notch location.

The "baseline" CTOD test following the requirements of API 1104 was done with the fatigue pre-crack length requirements of BS 7448: Part 2 [4]. This was to establish what may be considered as baseline results.

A set of specimens were extracted from the "first quarter" encompassing the 11 to 2 o'clock region, after considering indications detected during UT examination. The WCL specimens were extracted from the 12 to 1 o'clock region, while the HAZ specimens were extracted from 11 to 12 o'clock. The specimens were then machined to standard geometry dimensions (Bx2B) of, BS 7448: Part 2. (The standard test procedures for pipeline girth weld testing, namely API 1104 and CSA Z662, refer to BS 7448 for CTOD testing guidelines).

The machined samples had a surface ground finish on the load line and support surfaces that enabled macro-etching. This revealed the weld metal and the HAZ in order to accurately mark the through thickness notch/fatigue pre-crack locations along the required weld position following guidelines in Clauses 6.1 and 8.2 in BS 7448: Part 2. Integrated knife edges were machined into the specimens to allow the use of a clip gauge for the measurement of Crack Mouth Opening Displacement (CMOD). An EDM notch was then placed at a pre-determined depth using a 0.01 mm wire in a direction that was opposite to the direction of welding.

The weld centerline notch location was at the center of the hybrid portion of the weld. The heat affected zone notch was placed as to sample the HAZ at the fusion line of the HLA portion of the weld, noting that this notch location also sampled a portion of the cap pass deposited with laser assisted GMAW (see Fig. 5). CTOD dimensions for the X80 and X100 specimens are presented in Table 1.

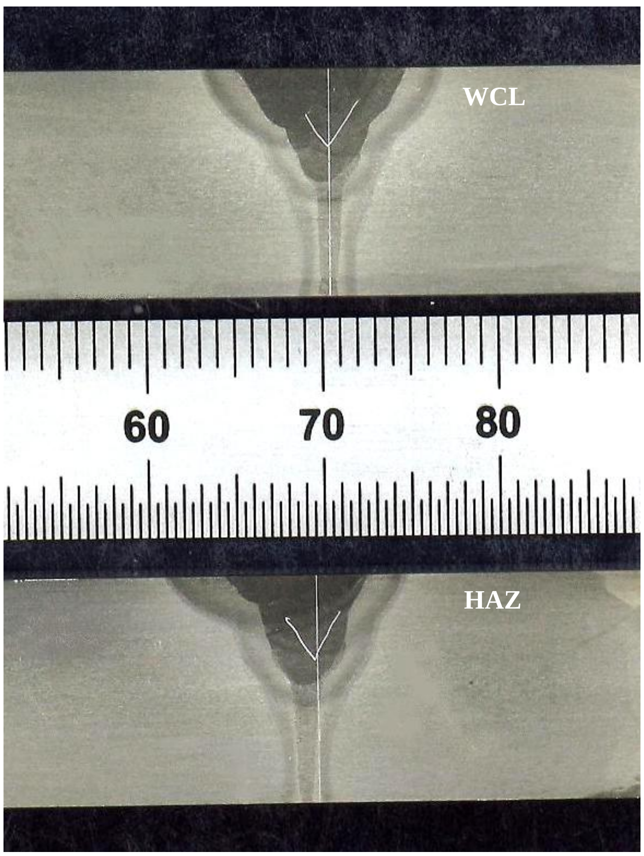

Figure 5: Typical placement of the through thickness notch for CTOD specimen blanks from X100 pipe.

Table 1: CTOD Specimen Dimensions

Pipe #*	Grade	Width (W) [mm]	Thickness (B) [mm]	Notch (M) [mm]
500	X100	25.7	12.7	10.4
501	X100	25.4	12.6	11
506	X80	16.8	8.39	6.9
506	X80	16.6	8.29	6.8

* The pipe numbers are for the purpose of tracking pipe welding records and therefore retained. They have no specific relation to testing, except to record that the specimens did not come from the same pipe.

TESTING PROCEDURES AND RESULTS

Tension Tests

The AWM strip tension and round bar tests (Hounsfield) were performed at quasi-static loading rate using a ramp rate of 1 mm/min and 0.4 mm/min, respectively. These tests were conducted at The Materials Assessment Lab, CANMET, Ottawa, where the testing was done at ambient temperature (23°C). For strip tension tests, the specimen elongation was monitored using a 25 mm gauge length extensometer, whereas for the Hounsfield specimen elongation was monitored using cross-head displacement. This variation was required because the specimen length (25 mm) and gauge length (approximately 10 mm) of the Hounsfield specimens were too small to mount an extensometer that would obtain reliable results. Testing was performed using a servo-hydraulic test frame under displacement control.

Strip tension results showed that there were minor variations in both yield and tensile strengths as the specimen location moved clockwise from the 12 o'clock position.

The Hounsfield tests were only carried out in the first quarter (11 to 2 o'clock) and only for the X100 pipe. The results showed about a 100 MPa lower value for the yield strength when compared to the strip tension specimen results. The lower value is likely a result of lower yield strength in the GMAW region compared to the HLA weld potion. The welds were over-matched.

Charpy Tests

The testing of both HAZ and WCL specimens was performed in accordance with ASTM E23 using a 400 J capacity NIST calibrated Satec Charpy impact tester. The specimens were cooled in a controlled temperature immersion bath, and the temperature was checked using a NIST calibrated digital instrument. The aim of the Charpy testing was to determine the temperature at which the specimens would undergo a ductile to brittle transition.

The clock positions 12, 3, 6 and 9 were identified by numbering the samples A, B, C and D respectively. The impact energies absorbed by both the WCL and HAZ specimens are provided in Fig.'s 6 and 7, which display the reduction in absorbed energy with a decrease in test temperature.

Two different "trends" were observed as described below (see Fig. 6 – note that only 12 and 3 o'clock results are presented as the results for the 6 and 9 o'clock showed similar behaviour). The fracture transition temperature for the 12 and 6 o'clock positions were interpreted to be -40°C, while the 3 and 9 o'clock positions transition temperatures were interpreted to be at -10°C. In other words, a higher fracture transition temperature was observed for WCL specimens from the 3 and 9 o'clock positions. It can be seen that the 3 o'clock position (507B) show gradual fracture transition behaviour when compared to the 12 o'clock positions, where abrupt fracture transition is observed (507A).

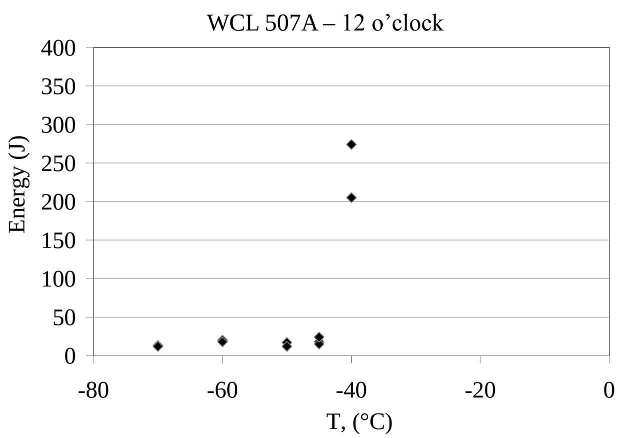

Figure 6a: WCL Charpy transition results.

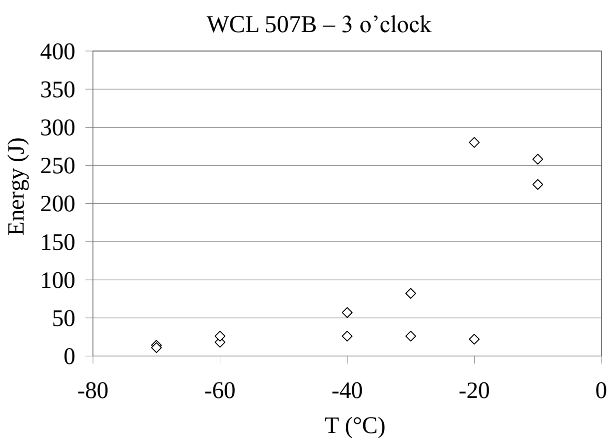

Figure 6b: WCL Charpy transition results.

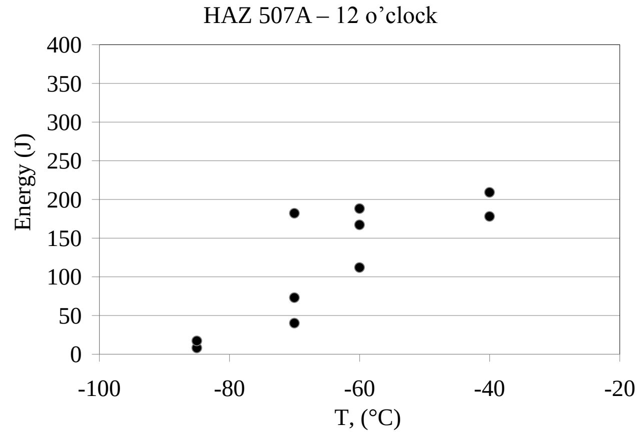

Figure 7a: HAZ Charpy transition results.

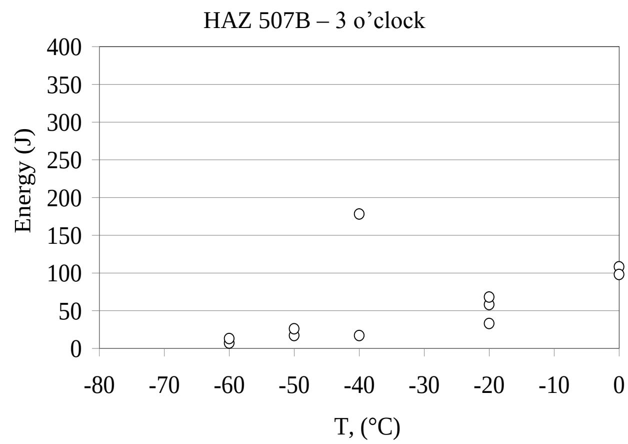

Figure 7b: HAZ Charpy transition results.

Light optical microscopy confirmed that all notch locations were positioned in their intended locations. Fig.'s 8 and 9 represent typical notch placement for the WCL and the HAZ notch locations, respectively. (*Note that this is a section plane normal to the view presented in Fig. 4 and it is at the mid-thickness plane of the specimen*). Deviation of the fracture path from the notch placement position was also observed in some of the specimens. Fig. 9 shows deviation of the fracture to the weld soon after fracture initiation at the intended HAZ. This is likely to have had an effect on the results presented in Fig.'s 6 and 7.

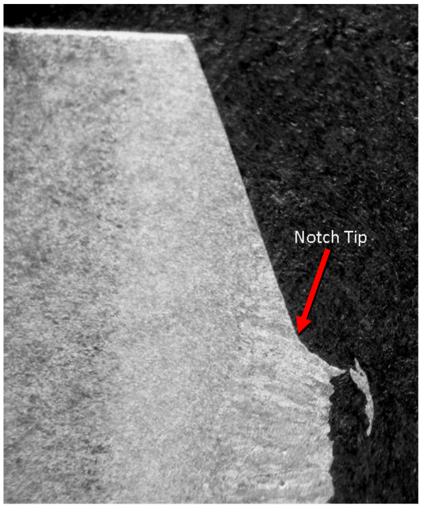

Figure 8: Typical notch placement for WCL samples at mid-thickness plane.

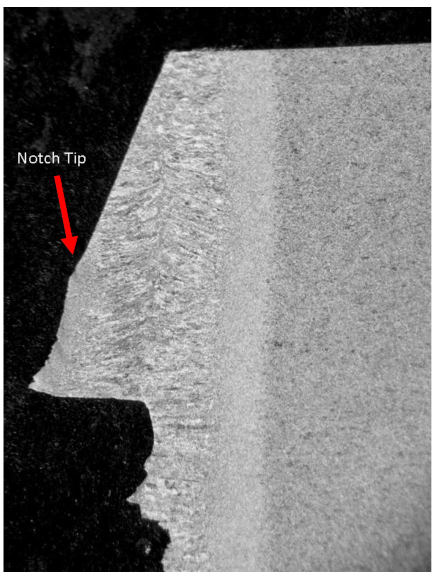

Figure 9: Typical notch placement for HAZ samples at mid-thickness plane.

CTOD Test

Prior to pre-cracking, each specimen was laterally compressed by approximately 0.5% thickness (B dimension) of the specimen. This lateral compression was conducted to reduce the variation of the weld residual stresses in the through-thickness direction (B), so as to help promote straight and even fatigue crack-front growth following the guidelines in BS 7448: Part 2; Annex D.

Each of the Bx2B geometry CTOD samples were then fatigue pre-cracked to approximately half the depth of the sample (i.e. a/W = 0.5). For the specimens of pipe 500, this meant an average fatigue crack growth in the range 2 to 2.5mm. For the specimens of pipe 501 and 506, this meant an average fatigue crack growth in the range of 1.2 to 1.7 mm. For crack initiation, the maximum stress intensity factor (K_f) was kept below that allowed in BS 7448: Part 1 [5], and the minimum to maximum load ratio (R-ratio) was kept at approximately 0.1. After crack initiation, fatigue pre-cracking was performed in three additional stages for specimens from pipe 500 (compared to two additional stages for specimens from pipe 501 and 506). The maximum K_f value was kept below the maximum value allowed in BS 7448: Part 1, as calculated from the compliance measurements during the automated pre-cracking process. This usually ensures that the final pre-cracking load is below the maximum allowed in the validity check, which is performed from the average crack length measured after the completion of the CTOD test.

The specimens were enclosed in an environmental chamber and cooled by liquid nitrogen to the required temperature. The atmosphere was monitored by attaching a thermocouple to the specimen. After the temperature had stabilized for a minimum period based on thickness (B in Table 1), the specimens were then loaded at a quasi-static rate ($\sim 1.3 MPa\sqrt{m}\ s^{-1}$).

The load and the clip gauge displacements were digitally acquired for the duration of the test. The test was then stopped once a fracture instability event was detected from the Load-CMOD curve, or a maximum load plateau was reached and surpassed. During testing, the Load-CMOD plot was displayed in real time on a computer screen, displaying the progress of the test. Later, the acquired data was used to determine the critical CTOD from the input of specimen dimensions; the measured fatigue crack length and material properties. Any audible "pop-in" detected during the progress was noted. After test completion, each specimen was immersed in liquid nitrogen (-196°C) and fully fractured to expose the fatigue crack and any subsequent growth that may have occurred during the CTOD test. Fatigue crack depth measurements were made in accordance with BS 7448: Part 1.

Table 2 shows the results for the tests performed at -5°C. The CTOD was calculated by adding the elastic and plastic CTOD as specified in Clause 12.1 of BS 7448: Part 2. The failure type for each test was determined by observing the crack growth as displayed on the fracture face of the specimen and the Load-CMOD curve. The failure types are when a maximum load plateau is reached and surpassed (δ_m type), or when fracture instability event occurred (δ_u or δ_c type). Failure type δ_u is when some crack growth or shear lip is observed in the fracture face and δ_c is for fracture event from the fatigue crack tip. Type δ_c* is when a pop-in is detected as specified in BS 7448: Part 1. Finally, the required validity checks were performed in accordance with BS 7448: Part 2. For pipe 500 tests, the validity requirements were met, while as for pipes 501 and 506 the minimum fatigue crack length requirement (1.3mm) was not met. This will further be addressed in the discussion of the results.

Table 2a: CTOD Results at -5°C for WCL Test Location.

Pipe #	Sample ID	a_o/W	Total CTOD [mm]	Failure type
500	12-W1	0.480	0.222	δ_m
	12-W2	0.491	0.199	δ_m
	12-W3	0.490	0.221	δ_m
501	12-W1	0.482	0.222	δ_m
	12-W2	0.481	0.269	δ_m
	12-W3	0.481	0.214	δ_m
506	1-W	0.491	0.117	δ_u
	2-W	0.492	0.042	δ_c*
	3-W	0.497	0.279	δ_m

Table 2b: CTOD Results at -5°C for HAZ Test Location.

Pipe #	Sample ID	a_o/W	CTOD [mm]	Failure type
500	12-H1	0.474	0.257	δ_m
	12-H2	0.476	0.203	δ_m
	12-H3	0.474	0.183	δ_m
501	12-H1	0.481	0.213	δ_m
	12-H2	0.482	0.232	δ_m
	12-H3	0.470	0.244	δ_m
506	1-HZ	0.467	0.113	δ_u
	2-HZ	0.480	0.379	δ_m
	3-HZ	0.483	0.318	δ_u

DISCUSSION

Tension Tests

It was possible to machine and successfully perform strip tension tests with the specimen geometry presented in Fig. 2. Stress-strain curves could also be obtained from the results. The gauge section though extremely narrow in the weld width dimension, was found to be sufficiently rigid to perform testing in a servo-hydraulic frame.

The lowest yield stress was above 830MPa for welds made in X100 pipe welds and therefore indicates that producing overmatched welds were feasible. Even the cap and fill region of the weld made by laser assisted GMAW had a yield stress of more that 730MPa, thus producing a weld strength that is overmatched for X100 pipe. It is however acknowledged that the Hounsfield specimen removed form the cap and fill region does not provide representative tensile properties for the HLA weld.

Charpy Tests

The results presented in Fig. 7 for the HAZ testing indicate, as for weld metal, that the fracture transition temperature is higher for the 3 o'clock position, implying a decrease in impact toughness for this clock position. (Similar results were observed for the 9 o'clock position.)

The reduction in toughness for the weld metal at the 3 and 9 o'clock positions has not been established, although the symmetrical results, with respect to clock position, suggest that the arc, laser, and shielding gas environments differ at two locations along the pipe circumference. Some scatter in the impact energy values were recorded, which is typically observed at the fracture transition temperature region in ferritic microstructures. Scatter could also be associated with the narrow cross sectional weld profile and due to the crack path deviating from the intended Charpy notch location, such as from the HAZ to the weld metal, as shown in Fig. 9.

The experience gained from this investigation proposes that a press-notched procedure, similar to that provided in ASTM E604 [6], be modified and implemented during Charpy specimen preparation of HLAW specimens. It is likely that the introduction of a pressed notch will then reduce the initiation energy, by strain hardening the material in the intended location (i.e. the root of the Charpy notch). This process is expected to potentially minimize crack path deviation. The effectiveness of the pressed notch is currently being explored by the authors.

CTOD Tests

The decision to use a shorter fatigue pre-crack than what is specified in BS 7448: Part 1 was primarily to decrease the likelihood of the fatigue crack tip extending to outside the intended test location. This becomes more likely in the very narrow hybrid laser portion of the weld. An example of minor fatigue crack deviation (after magnetic particle inspection, MPI) is presented in Fig. 10.

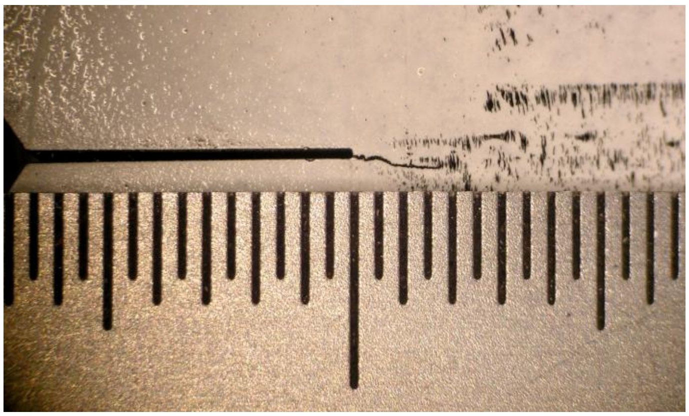

Figure 10: Fatigue crack marked by MPI at the specimen surface.

ASTM E1820-06 [7]; standard for measurement of fracture toughness, allows shorter fatigue crack depths, in accordance with Clause 7.4.5 (Fatigue Pre-Cracking Procedure). The minimum crack length prescribed is 0.6 mm or 0.025B for a narrow notch. For specimen sizes given in Table 1 the applicable crack length is 0.6 mm.

For pipe 506 (X80) the average fatigue crack depths for the specimens (in Table 2) were in the range of 1.1 to 1.45 mm. The minimum fatigue crack lengths were between 0.81 to 1.02 mm; therefore meeting the requirements of ASTM E1820-06. Similarly, for pipe 501 (X100) the average fatigue crack depths for the specimens (in Table 2) were in the range of 0.93 to 1.24 mm. The minimum fatigue crack length was between 0.67 to 0.98 mm and therefore the requirement for this set (i.e. 0.6 mm), was also met

For both sets of specimens removed from 11 to 2 o'clock region for the X100 pipe the maximum load plateau was reached and surpassed (δ_m behaviour). This indicates that the shorter fatigue crack length did not affect the δ_m behaviour. Test were also performed at -40°C, but are not reported in this paper. They also produced similar results for the short fatigue crack length and the standard fatigue crack length in the case of specimens with the notch in the weld metal.

In the tests performed with the notch in the HAZ, at -40°C, one of the tests with the standard fatigue crack length resulted in δ_c behaviour. The fracture face of the specimen is presented in Fig. 11. The fracture surface displays a cleavage (brittle) fracture event (marked by the arrow) and is associated with the sudden load drop that occurred during the test.

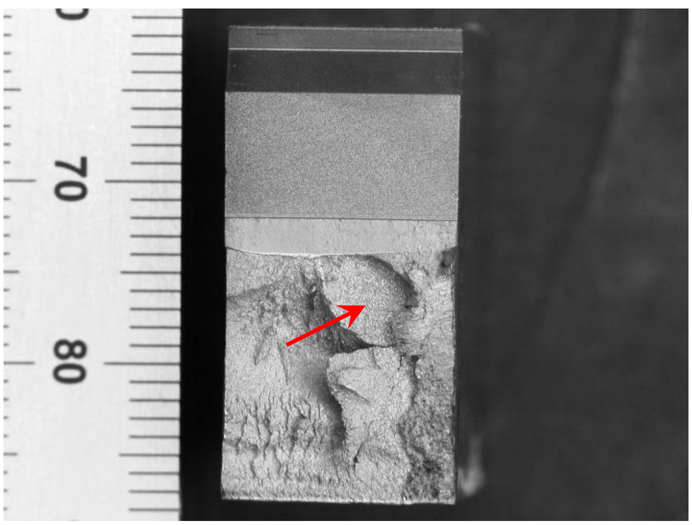

Figure 11: Fracture surface of a test that produced an instability event.

Triplicate CTOD tests were also conducted using API 1104 (Annex A) guidelines at the start of the program to establish "baselines" at a test temperature of -5°C for both pipe grades. The pipes were used to extract the CTOD specimens from specified locations, i.e. one each at 12, 3 and 6 o'clock. For the X100 pipe all three test specimens produced δ_m behaviour and therefore similar to the results presented in Table 2. For the X80 pipe, different behaviour was observed for the WCL specimens as given in Table 3, while the HAZ specimens from the three locations resulted in δ_m behaviour, reaching or surpassing a maximum load.

It needs be noted that only one test was done for each location. These results may be compared with those in Table 2 and it can be seen that the weld metal test at the 12 o'clock location (12W) produced fracture instability (δ_u), while the three specimens from pipe 506 (X80 pipe) resulted in three fracture types. In the case of the HAZ test, 12H has δ_m behaviour while the results presented in Table 2b display both δ_m behaviour and fracture instabilities (δ_u).

Overall, the results from X100 pipe displays δ_m behaviour both in the "API 1104 specimens" and those presented in Table 2, whereas, results from X80 pipe displays fracture transition behaviour for the weld metal at -5°C. For the HAZ tests the same behaviour observations may be made for the X100 pipe, although, for the X80 pipe there is apparently a difference noting that only one test is available in Table 3 for the 12 o'clock position.

Table 3: CTOD Results for X80 pipe at -5°C for API 1104 test locations.

Notch Location	Sample ID	a_o/W	Total CTOD [mm]	Failure type
WCL	12W	0.527	0.123	δ_u
	6W	0.513	0.228	δ_u
	3W	0.525	0.141	δ_c
HAZ	12H	0.523	0.427	δ_m
	6H	0.506	0.446	δ_m
	3H	0.536	0.276	δ_m

It also has to be noted that lateral compression was employed for the X100 samples to help promote straight and even fatigue crack-front growth following the guidelines in BS 7448: Part 2, Annex D for all of the testing. The results presented in Table 3 were generated without lateral compression. This was because the through-thickness residual stresses are usually not large for specimen thicknesses less than 12mm, as was the case for X80 specimens (see Table 1). In order to employ the short fatigue crack length and obtain a straight fatigue crack front, it was decided to employ lateral compression after crack front observations made from tests reported in Table 3. The improvement in the fatigue crack front straightness is presented in Fig. 12.

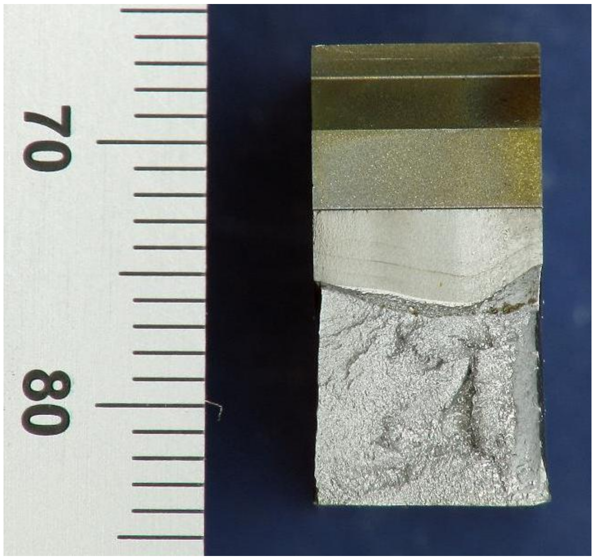

Figure 12a: Fracture surface of tests without lateral compression.

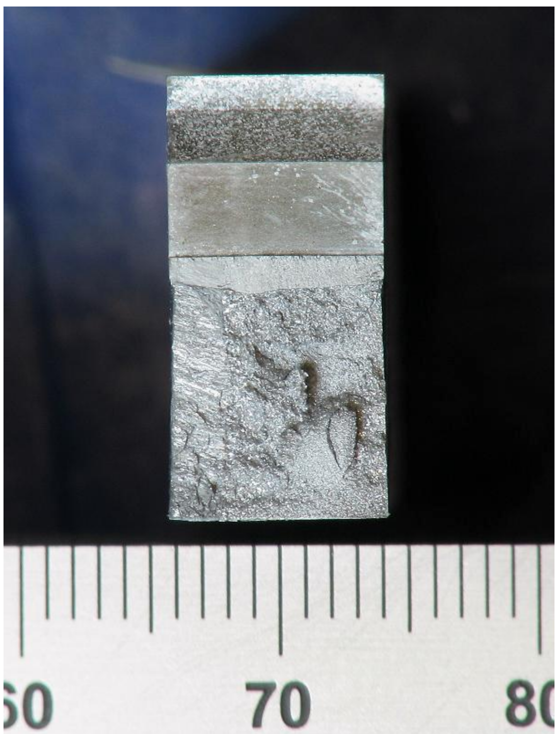

Figure 12b: Fracture Surface of Tests with lateral compression.

Post test metallography was performed to locate the tip of the fatigue crack front following guidelines in BS 7448: Part 2. Noting that this was done in selected test specimens, examples from notch placement in the weld and HAZ are presented in Fig. 13a. and Fig. 13b. respectively.

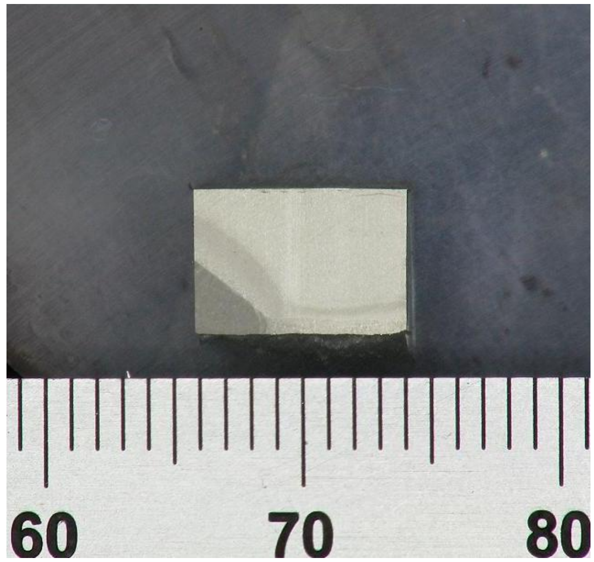

Figure 13a: Fatigue crack locations in weld

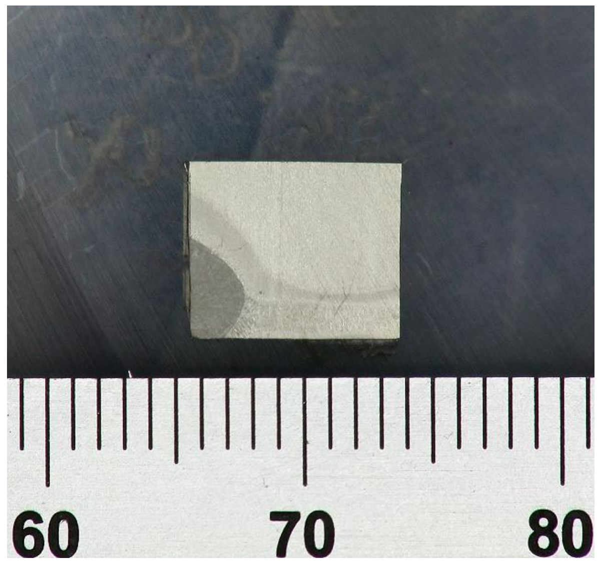

Figure 13b: Fatigue crack locations in HAZ.

Additional requirements of BS7448: Part 2, are of significance to the weld metal test results and are as follows:

- The degree of under-match versus over-match based on the yield strength ratio of the weld metal to base metal must be in the range 0.5 to 1.5. This criterion was met for both X100 and X80 pipe welds. The ratio was ~1.19 and ~1.36, for X100 and X80 pipe welds, respectively.
- The ratio of the weld width (*2h*) in the central 75% of the thickness of the specimen, to the ligament length of the fatigue cracked specimen (W-a_o) needs to exceed 0.2. This requirement was not met for X100 pipe weld and marginal results for X80 weld. This was expected due to the very narrow hybrid portion of the weld.
- These requirements are necessary for the weld metal CTOD estimate to be within a ±10% error.

SUMMARY

Observations from Charpy Testing

The objective was to observe any variation in fracture transition with clock position. The WCL specimens indicated that the transition temperature was higher at the 3 o'clock and 9 o'clock locations compared to the 12 o'clock and 6 o'clock. Also, while the results showed that the fracture transition occurred abruptly for tests results from 12 and 6 o'clock whereas for the 3 and 9 o'clock positions transition behaviour was gradual. The similarity of the fracture transition temperatures for the specimens with the notch in the HAZ to those for the WCL could be attributed to fracture path deviation in the narrow hybrid laser potion on the weld as shown in Fig. 9.

It is likely that the introduction of a pressed notch will reduce the initiation energy by strain hardening the material in the intended location, (i.e. the root of the Charpy notch). It is hoped that process will potentially minimize crack deviation. This is currently being explored.

Observations from CTOD Testing

At this stage, only the preliminary results are presented in the paper in terms of variation of fracture toughness with clock position. The finding from the preliminary work was the basis of developing a procedure for the CTOD tests, to be adopted for the narrow hybrid laser portion after considering currently established practices in CTOD test standards. The effect of using a shorter fatigue crack length was the primary focus of the effort. This is because of the HLA geometry may lead to the fatigue crack tip being outside of the intended weld or HAZ location.

Compared to standard fatigue crack depth and specimen preparation procedure, provided in guidelines (BS 7448: Part1) the following modifications were made for HLAW:

- Minimum fatigue crack depth reduced from 1.3mm to 0.6 mm
- Lateral pre-compression applied to specimens with thickness less than 10 mm in high strength welds to improve the fatigue crack profile to meet the cracks straightness requirements for validity.

These modifications did not produce any detectable effects on the fracture toughness results from specimens removed from the 11 to 2 o'clock segment of the pipe weld for both the X80 and X100 pipes. The effect of clock position on fracture toughness is currently being explored, adopting the test procedures developed in this paper.

One of the two additional requirements of BS7448: Part 2 of significance to the weld metal test results was not met. This is due to the narrow weld width of the hybrid portion of the HLAW. Thus the accuracy of the CTOD estimate could be outside of a ±10% error.

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