WELD METAL AND HEAT AFFECTED ZONE (HAZ) PROPERTIES OF TANKER HULL STRUCTURES

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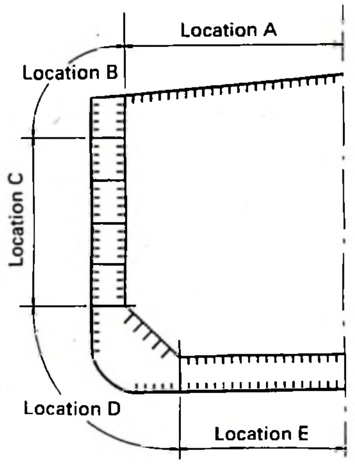
ABSTRACT

With the introduction of floating production, storage and offloading vessels (FPSOs) for processing hydrocarbons from remote subsea wellheads, concerns have been highlighted regarding the integrity of tanker hull structures for FPSO applications. Although construction of hull structures are in accordance with class rules. FPSOs are intended to remain on location during their field life without having to dry-dock for inspection or repair. Jack Still and Julian Speck provide an overview of a test programme conducted to assure the fracture resistance of a recently completed Afromax tanker hull destined for conversion to an FPSO.

It is common practice for the ship builder to specify the hull materials in accordance with the classification society rules. The materials normally selected for a Afromax tanker consist of Grades A and AH32 carbon-manganese steel. Owing .to the anticipated service conditions of the vessel, the outer hull materials were changed to Grades D and DH32. In addition, the thickness of the deck and the bottom of the hull, in Grade DH32, was increased by 3mm.

This upgrade in material was intended to provide improved resistance against fracture, i.e. resistance to the initiation of brittle cracks (fracture toughness) and crack arrest properties. Specific details of the composition and properties of hull steels are summarised in Table 1 and 2, respectively. Figure 1 illustrates the location of the material grades within the hull structure.



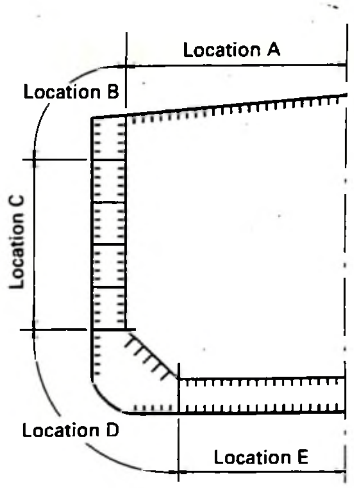
Location	ABS base material	Thickness mm
A (Deck)	Gr. DH32	19.5
B	Gr. DH32	19.5
C (Side shell)	Gr. D	17.5
D	Gr. DH32	19.5
E (Bottom)	Gr. DH32	19.5

SELECTION OF WELDING CONSUMABLES

The selection of welding consumables, was based on the weld metal Charpy impact toughness requirements matching the minimum Charpy impact toughness levels specified for the hull materials. Ship classification societies in this instance specify either Grade 2Y or 3Y consumables for welding Grades D and DH32 steels. The Charpy impact toughness requirements for 2Y consumables is 34J at 0° C which also meets the requirements for Grades A and AH32 steels. Grade 3Y consumables specify Charpy impact toughness requirements of 34J at -20°C, which satisfy the toughness rquirements for Grade D and Grade DH32 steels.

WELDING PROCEDURE TEST PROGRAMME OF WORK

Gas shielded flux cored arc (GSFCAW) and electro-gas (EGW) are the two main welding processes used during the construction of a tanker hull structure. Ceramic backing tiles are extensively used in conjunction with the above processes to enable single-sided welds to be produced, reducing the fabrication time. Figure 2 outlines the areas where GSFCAW and EGW are applied. Based on the use of the welding processes during construction of the hull structure, the weld test programme involved both Grades D and DH32 steels. The test plates included two GSFCAW consumables (AWS A5.29 E80T1-K2') from two consumable manufacturers



Location	Welding	Application	Position
A (Deck)	GSFCAW (Root)	Semi-automatic	1G (Ceramic backing)
	GSFCAW	automatic	1G
	GSFCAW	Semi-automatic	1G (Ceramic backing)
B	GSFCAW	Semi-automatic	1G (Ceramic backing)
	GSFCAW	Semi-automatic	1G (Ceramic backing)
C-(Side shell)	EGW	Automatic	3G (Ceramic backing)
D	GSFCAW	Semi-automatic	3G (Ceramic backing)
E(Bottom)	GSFCAW (Root)	Semi-automatic	1G (Ceramic backing)
	GSFCAW	Automatic	1G
	GSFCAW	Semi-automatic	1G (Ceramic backing)

(hereafter referred to as consumables A and B), and one EGW consumable, ie consumable C (AWS A5.26 EG70T-2[2]).

The welding procedure test plates were welded as single-sided welds in the vertical position, using a ceramic backing strip. Examples of the welding parameters recorded for both GSFCAW and EGW are presented in Table 3. No preheat was applied, ie material temperature was recorded as ambient. The maximum interpass temperatures recorded were 88 and 21°C. for the GSFCAW and EGW, respectively. Typical weldment macrosections for both welding processes are shown in Fig.3.

CHEMICAL ANALYSES OF PLATE MATERIALS AND WELD METALS

The base metal and weld metal chemical analysis results are presented in Table 4. The GSFCAW welds contained additions of nickel, titanium, and boron. Both the nickel and the boron elements were in sufficient quantities to improve fracture toughness. The titanium is available for the dual purpose of promoting fracture toughness, while also acting as a sacrificial element to combine with nitrogen and thereby protect the boron addition. The weld metal chemical analysis of the EGW contained a relatively high manganese and molybdenum content.

MECHANICAL PROPERTIES OF THE TEST PLATE WELDMENTS

The mechanical properties of the test plate weldments are presented in Table 5. The Charpy impact toughness values of the weld metal for both welding processes and material grades were found to satisfy the minimum requirements of the classification society. Weld (HAZ) Charpy impact tests on specimens notched one millimetre from the fusion boundary, measured impact energy values well above the minimum specification requirements for the base material. The lowest HAZ Charpy impact toughness results were recorded in test plate No. 3, in the Grade DH32 steel. The reason

Table 1 : Chemical properties and product analysis

Grade	Chemical analysis													
	C	Si	S	P	Mn	Ni	Cr	Mo	V	Ti	Cu	Nb	Al Soluble	N
Chemical composition (All values quoted are maximum unless otherwise stated)														
D	0.21	0.10/0.35	0.035	0.035	0.60min	SEE NOTE 1					SEE NOTE 1			
DH32	0.18	0.10/0.50	0.035	0.035	0.90/1.60	0.4	0.2	0.08	0.05/0.10	0.02	0.035	0.20/0.05	0.015min	
Typical product analysis														
D	0.14	0.26	0.004	0.02	1.27	0.02	0.003	Tr	-	-	0.01	-		
DH32	0.14	0.39	0.008	0.014	1.22	0.02	0.03	Tr	-	-	0.02	0.02	0.039	

Note 1
When Ni, Cr, Mo and Cu to be reported. When the amount does not exceed 0.02% these elements to be reported as <0.02%

for the low value was not specifically investigated. (It was noted that the recorded welding parameters for this test plate were similar to that of the other test plate welds while the parent material composition showed no inrregularities.) The HAZ properties of the EGW welds measured comparatively higher values of impact toughness.

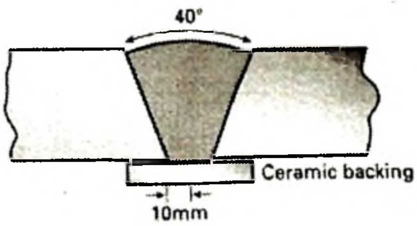
Fig. 3a Typical gas-shield flux-cored arc weld (GSFCAW) (4x)

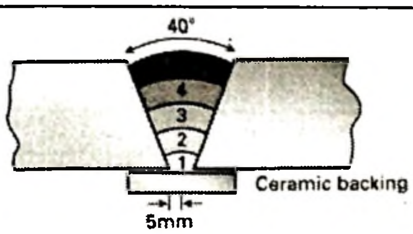
Fig. 3b Typical electro-gas weld (EGW) (4x)

Table 2 : Mechanical properties for hull materials

Mechanical properties					Charpy impact properties		
Grade	Thickness, mm	UTS Min, N/mm2	Yield min, N/mm2	Elongation, Min %	Test temperature, °C	Longitudinal, joules	Tranverse, joules
Specification							
D	<50	400	235	22	-20	27	20
DH32	<50	440	315	22	-20	34	24
Typical product mechanical properties							
D	17.5	461	318	28	-20	210	
DH32	19.5	541	449	25	-20	206	

Table 3 : Electro gas welding and gas shield flux cored are welding procedures





Bead	Diameter mm	Polarity	Amps	Volts	Weld Speed, cm/min	Heat input, KJ/cm	Bead 5 layers	Diameter mm	Polrity	Amps	Volts	Weld speed, cm/min	Heat input KJ/cm
1	1.6	DCRP	410	38	9.6	97.4	1	1.2	DCRP	210	27	11.6	29.3
							2	1.2	DCRP	210	29	19.6	18.6
							3	1.2	DCRP	220	32	14.8	28.5
							4	1.2	DCRP	200	27	15.7	20.6
							5	1.2	DCRP	190	27	13.2	23.3

Electro gas welding (EGW) Shielding gas	Gas shield flux cored arc welding (CSFCAW) shielding gas
Sheilding gas flow rate 25 litres/min using 99% CO_2	Sheilding gas flow rate 25 litres/min using 99% CO_2

Table 4 : Weld material and parent material chemical analysis

Plate No	C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Al	B
Weld metal														
1 (A)	0.06	0.37	0.012	0.015	1.27	1.41	0.03	<0.005	0.02	0.04	0.011	0.044	0.005	0.0062
2 (A)	0.06	0.42	0.009	0.015	1.20	1.45	0.03	0.005	0.01	0.005	0.009	0.041	<0.0003	0.0037
3 (B)	0.05	0.46	0.008	0.015	1.29	1.42	0.03	0.005	0.02	0.005	0.010	0.041	<0.0003	0.0039
4 (B)	0.05	0.34	0.013	0.014	1.22	1.45	0.03	<0.005	0.02	0.04	0.010	0.036	0.004	0.0053
5 (C)	0.07	0.48	0.008	0.019	1.82	0.02	0.03	0.19	<0.002	0.01	<0.002	0.017	0.013	0.0014
Plate material														
1	0.15	0.18	0.003	0.023	0.74	0.01	0.03	<0.005	0.005	0.005	<0.002	<0.002	0.026	0.0003
2	0.15	0.18	0.003	0.023	0.74	0.01	0.03	<0.005	0.005	0.005	<0.002	<0.002	0.024	<.0003
3	0.16	0.27	0.003	0.016	0.99	0.01	0.04	<0.005	0.005	0.005	<0.002	<0.002	0.022	<0.0003
4	0.16	0.27	0.005	0.016	0.99	0.01	0.04	<0.005	0.005	0.005	<0.002	<0.002	0.023	<0.0003
5	0.15	0.18	0.003	0.021	0.74	0.01	0.02	<0.005	0.005	0.005	<0.002	<0.002	0.025	<0.0003

(A) GSFCAW - Electrode A, (B) GSFCAW - Electrode B, (C) EGW Electrode C

Table 5 : Weld material machanical properties

Plate No.	All weld metal tensiles		Charpy impact tests (Test temperature -20°C)			Hardness test (load 10kg)			
	RP 0.02% N/mm2	Max stress, N/mm2	weld, Joules	HAZ, Joules	Parent material	HAZ	Weld metal	HAZ	Parent material
1 (A)	475	633	80-80-75	168-165-177	137	156	206	147	134
2 (A)	548	671	96-93-102	228-236-243	157	150	213	154	142
3 (B)	512	638	105-102-103	81-86-94	153	171	222	172	150
4 (B)	420	609	89-101-102	150-214-151	150	176	217	160	148
5 (C)	473	677	63-90-56	43-107-126	156	162	203	157	152

(A) GSFCAW - Electrode A, (B) GSFCAW - Electrode B, (C) EGW Electrode C

All weld metal tensile tests recorded 0.2% proof strengths of between 420 to 512N/mm^2, while the parent material tensile properties ranged from 304 to 383N/mm^2. A Vickers hardness survey carried out on weldments recorded hardness values of between 212-240, and 169-181, in the weld metal and HAZ respectively.

CTOD FRACTURE TOUGHNESS

Crack-tip opening displacement (CTOD) fracture toughness tests were performed for use in a fracture mechanics-based engineering critical assessment (ECA).[3] The results of the ECA were subsequently used to identify the maximum flaw (fatigue crack) size that the fatigue sensitive hull welds could tolerate, prior to failure by fracture.

Weld metal and weld HAZ CTOD tests were manufactured from all procedure test panels and tested in accordance with BS 7448.[4,5] The range and the appropriate value (δmat) of CTOD fracture toughness test results (at-10°C), for each of the test panels, are presented in Table 6. In general, the accuracy of a sample depends on its size and on the variability of the property measured. If a material is microstructurally homogeneous, the sample size can be small. If it is non-homogeneous, eg weld HAZ, the sample size must be large to be representative of the material.

Sets of six CTOD specimens were therefore tested for each weldment region. The 'appropriate' value of CTOD fracture toughness (δmat), for use in an ECA for failure by fracture, is subsequently defined as the second lowest result from the set.[6]

δmat for all of the test panels was above 0.100mm. The highest were measured in the parent materials, ie dmat>0.500mm. Both parent materials exhibited fully plastic (ductile) behaviour during testing. The failures of the weld HAZ specimens were also ductile, except for a few results from the HAZ of a FCAW panel (Grade D, E80T1-K2 (B), δmin=0.332mm) and the EGW panel (Grade D, E70T-2, δmin = 0.098mm). Post-test examinations revealed that the fracture event of the lowest HAZ CTOD result in the FCAW panel exhibited no tearing. The lowest HAZ CTOD in the EGW panel was found to be due to a significant pop-in, ie the arrest of a crack after it rapidly extends across a brittle microstructural region.

WELD METAL AND WELD HAZ METALLOGRAPHY

The weld metal and weld HAZ were metallographically examined from all of the test panels, ranging from 50 to 100X magnification. Examples of these microstructures are shown in Figure 4 (test plate No. 3, 19.5mm thickness, Grade DH32) and Figure 5 (test plate No. 4, 17.5mm thickness, Grade D) and comprised the following phases:

Table 6 : Summary of measured CTOD values at -10°C

Description	Region	δmin, mm	δmat, mm	δmat, mm*
ABS Grade D	Parent material	1.570	1.613	1.570
ABC Grade DH32	Parent material	0.702	0.778	0.721
Gr. D, FCAW, E80T1-K2 (1)	HAZ	1.050	1.231	1.105
	Weld material	0.265	0.594	0.325
Gr. D, FCAW, E80T1-K2 (2)	HAZ	0.332	1.281	1.056
	Weld material	0.160	0.709	0.226
Gr. DH32, FCAW, E80T1-K2 (1)	HAZ	0.427	0.558	0.443
	Weld material	0.404	0.603	0.421
Gr. D, FCAW, E80T1-K2 (1)	HAZ	0.098	1.487	0.578
	Weld material	0.131	0.408	0.214

δmat is the second lowest CTOD value in a set of six specimens

ENSURING QUALITY OF FPSO WELDS

The results of the materials test and inspection programs, over and above the class requirements introduced by the operator during construction,[6] were used in a fracture mechanics-based assessment to determine the maximum flaw size tolerable in the hull under in-service loading. Although this test programme was applied to a hull structure intended for conversion to an FPSO vessel, the principles could be applied to any vessel particularly tanker hull structures designed to operate in severe operating conditions.

4a.

4b.

5a.

5b.

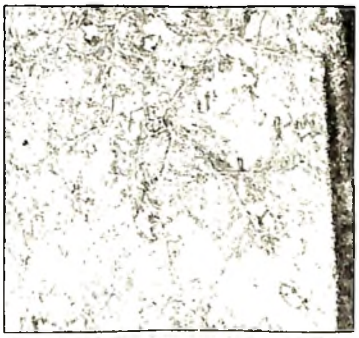


Fig. 4a. As-deposited and refined weld metal microstructure between two successive passes. The varying microstructural features are typical of multi-pass fusion welds, depending on the location within the weld.

Fig. 4b. Weld HAZ, fusion line and weld metal microstructure comprising re-crystallised, transformed and tempered zones within the HAZ.

Fig. 5a. As deposited microstructure at the outer edge of the weld towards the fusion line. These large islands increase in size with increasing peak temperature and increasing residence time.

Fig. 5b. Weld metal, fusion line and weld (HAZ). The HAZ microstructure exhibits enlarged areas of polygonal ferrite, a distinguishing feature of this comparatively high heat input process.