THE EFFECT OF THE CHEMICAL COMPOSITION AND HEAT TREATMENT ON THE TRANSITION TEMPERATURES OF THE LOW ALLOY C-Mn STEEL PLATES

JOZEF FILA and ZDZISŁAW ZATORSKI
Naval Academy, Gdynia 19, Poland

ABSTRACT

This paper presents the results of author's investigations on toughness and CTOD of normal St41-A and higher strength 15G2ANb-EH36 and 15G2ANb-E460T steel plates and structures. The wide variety of nonmetallic inclusions and microstructures within HAZ and tested weld metals were responsible for the variation of mechanical properties and effects in the crack tip opening displacement (CTOD) behaviour. The fracture events within the plastic zone occured at the matrix-particles decohesion stress at the critical distance ahead of the crack tip. The brittle fractures were not caused by the inclusions.

INTRODUCTION

The application of higher strength steels in commercial shipbuilding has, until relatively recently, been limited to the longitudinal elements of decks and bottoms of large vessels such as tankers, container ships and LNG carriers. More recently some structures of large tankers e.g. have been built with very high percentages of higher strength steels in the cargo tank area including the shell envelope, longitudinals and main transverse webs. These vessels have been built with steels of either 315 MPa or 355 MPa or 400 MPa yield strengths.

The offshore industry has tended to make wide use of higher strength steels in the range of 400-690 MPa. In general, fracture toughness testing is performed to evaluate lower bound fracture toughness and to select welding procedures or materials and consumables in order to avoid unacceptably low toughness zones in welded structure. These procedures normally incorporate both Charpy V notch testing and fracture mechanics tests such as the CTOD test [3].

MATERIALS

The investigations of the normal St41-A and higher strength 15G2ANb-EH36 and 15G2ANb-E460T steel plates and structures have been carried out [1,2]. The chemical composition of the tested steels is presented in Table 1.

Table 1. The chemical composition of the St41-A and 15G2ANb steels in pct.

Steel	C	Mn	Si	P	S	Nb
St41-A	0.22	0.26	0.81	0.011	0.031	-
15G2ANb	.14-.16	1.22-1.35	.30-.49	.011-.016	.018-.022	.28-.35

The nonmetallic inclusions were analysed by image analysis technique with the use of the quantimeter QTM-360B type. The results varied on the 95% confidence level as follows :

inclusion area fraction, A_A : 0.067-0.132%,
particles per sq. mm, N_A : 195-955, mm^{-2},
mean size of inclusion, L_2 : 2,85-6,62 μm,
max length of inclusion, L_Y : 3-250 μm.

The examples of the inclusion contents in tested plates are given in Table 2. The steels were prepared in the BOF process and normalized (15G2ANb-EH36 steel) or quenched and tempered (15G2ANb-E460 steel), and melted (electric process) and normalized (St41-A).

Table 2. The nonmetallic inclusion contents of the St41-A and 15G2ANb steel plates

Steel/ thickness mm	Max. length L_Y μm	particles persq. mm N_A mm^{-2}	Aver. area fraction, A_A %	Mean size, L_2 μm	Inclusion type
15G2ANb 12 mm	75	9,52	0,0100	2,64	sulphides and silicides
	250	19,52	0,0137	2,62	
	20	181,17	0,1741	1,80	
15G2ANb 28 mm	20	31,41	0,0394	2,49	sulphides and oxides
	20	34,51	0,1208	2,35	
	20	38,93	0,0481	2,29	
St41-A 12 mm	50	16,87	0,1596	14,47	silcides and oxides
	125	31,57	0,0964	5,23	
	50	30,82	0,1157	3,13	

Any particular feature of interest can be affected by small variations in welding procedure and joint geometry. There were investigated examples of two welds, each with a straight sided heat affected zone (HAZ) and one with 'K' preparation and the second one with 'half V'- using two different welding methods and 12-28 mm-steel plates.

The weldments of the St41-A steel plates were made by using EB1.46 electrodes. Experimental submerged arc welding (SAW) and manual metal arc welding (MMAW) were applied on the 15G2ANb steel plates at various combinations of consumable wires, fluxes and electrodes. The welding conditions are given in Table 3. From the parent material and from the welded plates the fracture taughness and Charpy impact test square pieces and tensile round ones (which included both weld metal and HAZ) were machined.

Table 3. The welding conditions and filler metals for the 15G2ANb-EH36 and 15G2ANb-E460T steel plates

Steel	Filler metal	Current A	Voltage V	Welding speed cm/min	Heat input kJ/cm	Weld metal designation
15G2ANb-EH36	SpG4N+ TASt1/	550-650	27-29	43-35	19-31.4	SA
	EB1.46	130-240	22-23	-	12.4-30	S
15G2ANb-E460T	SpG4N+ TASt1/	500-650	27-29	43-35	19-31.4	SA
	EB3.50Ni2	130-240	22-23	-	12.4-30	SNi

CTOD and J-INTEGRAL TEST PROCEDURES

CTOD tests were conducted according to BS 5762:1979 "Methods for Crack Opening Displacement Testing".

The three-point bend specimens of the preferred geometry (B by W=2B by S=8B) were used exlusively. They were fabricated from the St41-A, 15G2ANb, 10G2AVNb-EH36 and 15G2ANb-E460T steels. The 100 kN universal closed-loop fatigue testing machine type MTS 810.12 was used. Knife edges for the clip-gauge were machined into the specimens in every case. Load and clip-gauge displacement as well as load and line displacement signals were transmitted directly from the test machine to a X-Y1-Y2 plotter. Low temperature tests were carried out inside a cooling tank mounted on the hydraulic actuator. As a heat transfer medium alcohol was used. Below - 73°C, liquid nitrogen was circulated through copper coil submerged in alcohol. Above-73°C, solid carbon dioxide was used. There are currently no specific standards for fracture mechanics testing of weldments.

The wide variations of microstructures within HAZ and weld metal of welded joints of St41-A and 15G2ANb steels were responsible for a variation on mechanical properties and effects in the crack tip plastic zone and of CTOD behaviour.

The through thickness CTOD specimens for weld metal and HAZ toughness evaluations were prepared according to the recommendations of the Comission X of the International Institute of Welding (IIW). Critical CTOD values are reported below according to the type of failure. Brittle initiation and fracture propagation are calculated as δc values at the Vc displacement.

Fractures occured in a ductile fibrous "thumbnail" followed by brittle cleavage or mixed mode propagation are calculated as δu values at the Vu displacement.

For upper shelf ductile fractures the CTOD values are calculated as δm values at V_M displacement. BS 5762:1979 provides the following formula for analyzing the load clip-gage displacement record to obtain the critical CTOD value

$$\delta = \frac{K^2(1-v^2)}{2\sigma_{YS} E} + \frac{0,4(W-a)\,V_p}{0,4W + 0,6a} \qquad (1)$$

where variable used in this equation are :

δ - crack tip opening displacement (CTOD), mm
a - crack length, mm
B - specimen thickness, mm
W - specimen depth, mm
E - modulus of elasticity, MPa
v - Poisson's ratio
K - stress intensity factor at maximum load, MPa √m
σ_{YS} - yield stress, MPa
Vp - plastic component of clip-gage displacement, mm.

For δc and δm critical CTOD values, the crack length is taken as the end of the fatigue crack. Test preparation, specimen machining and fatigue cracking were made at the ratio of a/w=0,35 and dimensions B•W=10•20 and 14•28 mm for the materials as in Table 2.

The J_{IC} integral values were calculated according to PN-88/H-04336 from the following equation :

$$J = \frac{2A}{(W-a)\,B} \qquad (2)$$

where "A" is the area under the load vs. load - line displacement record [4].

CTOD AND J_{IC} FRACTURE TEST RESULTS

The resultes of CTOD testing of three materials and weldments are shown in Figs.1 and 2 and in Table 4. All the CTOD vs. temperature transition curves have roughly the same shape and for the purpose of description these can be divided into the following four regions : 1) lower shelf, 2) lower transition, 3) upper transition, and 4) upper shelf. The lower transition region is characterized by a brittle fracture with no visible evidence of prior stable cracking characterized by δc values. The development of the plastic the hinge transition region indicates an elastic-plastic fracture behaviour. In the upper transition region, the failure initiates by stable ductile tearing recognizable by coarse fibrous "thumbnail", which is followed by fast brittle cleavage or mixed mode propagation characterized by δu values. The upper shelf region characterizes itself by fibrous ductile tearing over the entire surface and δm values [6].

Table 4. Results of the CTOD testing of the St41-A, and 15G2ANb-EH36 and 15G2ANb-E460T steels and weldments

Steel type/ heat treat.	Filler metal	Spe- cimen	Upper trans. temp. °C	Lower trans temp. °C	δm mm	δ=0,1 mm temp. °C	J_{IC} MNm^{-1}
St41-A normal. NDT=-25 -30	-	4RW	-40	-90	0.115	-45	0.370
	-	4RP	-20	-80	0.160	-55	0.192
	EB1.46	4S	-40	-90	0.110	-67	0.228
	1-2mm HAZ	4C	-60	-75	0.117	-65	0.309
15G2ANb-EH36 normal. NDT=-45 -60	-	15W	-110	<-120	0.166	-110	0.448
	EB1.46	SNi	-20	-50	0.15	-20	-
	0.1mm HAZ	SC	-80	-95	0.15	-75	-
	SPG4N/ TASt1	SA	-20	-30	0.15	-20	0.222
	2 mm HAZ	N2C	-70	-90	0.15	-75	-
15G2ANb-E460T quenched and temp-red NDT=75°C		16UW	-110	<-110	0.206	<-110	0.463
		16UP	<-110	<-110	0.202	<-110	0.290
	1 mm HAZ	U1C	-80	-95	0.171	-75	0.361
	3 mm HAZ	U3C	<<-110	<-110	0.201	<<-110	-
	5 mm HAZ	U5C	<-100	<-110	0.225	<-110	0.347
	EB3.50Ni2	SNi	-30	-80	0.175	<-50	0.332
	SPG4N/ TASt1	SA	-20		0.075	<-50	0.222

W,P - longitudinal and transverse specimens,

The change from the brittle fracture of the lower transition region to the visible fibrous "thumbnail" of the upper transition region occurs at δu approximately 0,07 mm for 15G2ANb

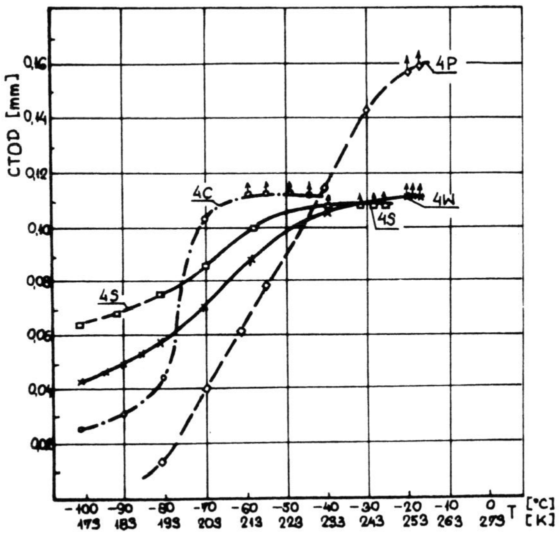

Fig 1. CTOD versus temperature curves for the St41-A steel and weldment. Specimen 10•20•80 mm. 4W - longitudinal specimen, 4P - transverse specimen, 4C - HAZ notches machined 1-2 mm from fusion zone (FZ), 4S-weld metal, EB1.46.

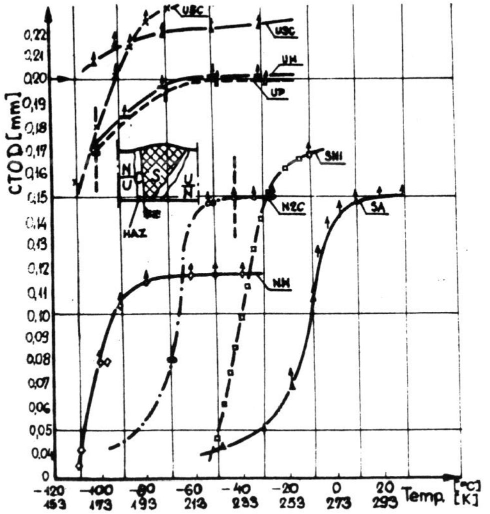

Fig 2. CTOD versus temperature curves of the 15G2ANb-EH36 and 15G2ANb-E460T steels and weldments. Specimen 14•28•112 mm : NW - normalized 15G2ANb-EH36 steel, longitudinal specimens, N2C - 15G2ANb-EH36 steel HAZ, notches machined 2 mm from FZ, UW/UP - quenched and tempered 15G2ANb-E460T steel, longitudinal UW) and transverse (UP) specimens, U3C/U5C - HAZ, 15G2ANb-E460T steel, notches machined 3 mm (U3C) and 5 mm (U5C) from FZ, SNi - weld metal, EB3.50Ni, SA - weld metal, SPG4N/TASt1.

steel and at 0,10 mm for St41-A steel.

Convenient criterion of CTOD=0,10 mm for offshore quality structural steels [3] indicated that low toughness of the weld metals is followed by the HAZ's and by that of parent metals of the normalized and quenched and tempered steels toughness of the 15G2ANb The recommended minimum 15% grain coarsed HAZ at low CTOD (<0.03 mm) of the fatigue crack tip of the through thickness CTOD test was partly controlled. From the other hand, because K_{IC} determined the linear elastic plane-strain behaviour, and J_{IC} integral determines the initiation of stable cracking, CTOD is the only fracture parameter in this lower transition region [6]. Analysis of the fracture micromechanisms on the CTOD specimens showed that voids are nucleated within the plastic zone around inclusions and second phase particles. The fracture events within the plastic zone occurred at the matrix-particles decohesion stress (the change of three - to two dimensional stress state around inclusions and second phase particles) at the critical distance ($X/S \approx 2$) ahead of the crack tip [5]. The CTOD values and plastic zone radiouses were correlated with the distances between inclusions above the ductile-brittle fracture transition temperatures. The L_Y length and the shape of inclusions along the crack were more effective than A_A volume parts for the initiation and growth of brittle fractures. These fractures were caused by critical stress at the plastic zone of the sizes one order higher than characteristic distances between the inclusions. The dimples size were one order lower than the characteristic distances. The dimples with the inclusions characterized the quenched specimens and the dimples with the inclusions and second-phase particles (mainly carbides) characterized the quenched and tempered 15G2ANb steel. The brittle fracture were not caused by inclusions.

CONCLUSIONS

An investigation of CTOD behaviour of the two normalized St41-A and 15G2ANb-EH36 ship steels and high strength quenched and tempered 15G2ANb-E460T steel to study the relationship among several toughnes parameters resulted in the following conclusions.

1. CTOD is the only fracture parameter applicable in the region between the plane-strain linear elastic behaviour (determined by K_{IC}) and ductile tearing initiation behaviour (determined by J_{IC}).
2. The tempered martensite microstructure showed higher δm values and lower upper transition temperatures than normalized microstructure of the 15G2ANb steel at determined inclusions limits.
3. The role of inclusions is significant in the plastic zone ahead of the crack tip.
4. Brittle fractures were not caused by inclusions.

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