EFFECT OF SIDE GROOVES AND ORIENTATION OF THE TESTPIECES ON COD VALUES OF A STRUCTURAL STEEL

H. M. Caminha Jr. and F. L. Bastian

The fracture properties of a high strength low alloy atmospheric corrosion resistant steel were studied using the COD testing method. Two testpiece orientations were employed. Side grooves were machined on some testpieces aiming to obtain values of COD at initiation from a single testpiece. This was not possible. The steel showed a high dispersion of COD values resulting from different fracture modes during the tests: cleavage, delamination and change from ductile to cleavage. These three fracture behaviours are analysed as functions of the microstructure of the steel.

INTRODUCTION

The crack opening displacement testing method (1) is nowadays widely used for assessing the fracture toughness of structural steels. However, it still presents some problems as the dispersion of the experimental results and the choice of a critical value – COD at initiation (δ_i) or COD at maximum load (δ_m) – from the test record. The dispersion of results, which is a common problem of materials in the elasto-plastic regime, appears to result, in the case of COD tests, from actual material property changes rather than from the testing method, which is already well developed (Harrison (2). In this respect, Johnston (3) suggests that these dispersions can follow a bimodal distribution whose branches result from the ductile and brittle contributions. In relation to the critical value of COD, both δ_i and δ_m present advantages and limitations. The main advantages of δ_i are: it appears to be a property of a material (4) and it does not depend on the geometry of the testpiece and loading mode (5). Its limitations are: it is difficult to be obtained (6) and it gives very conservative values for design purposes(7). On the other hand, δ_m is easily obtained and is a good design parameter (7), although it depends on testpiece thickness and geometry and also on the loading mode. In relation to the method of obtaining δ_i, some authors (8, 9) have suggested that side grooves on the testpieces could raise the stress triaxiality at the tip of the crack causing therefore δ_m to coincide with δ_i, at some critical conditions, and allowing δ_i to be obtained from a single test.

Also very important in a COD test is the orientation of the testpiece, since several authors (10, 11) have observed marked

(*) COPPE/Federal University of Rio de Janeiro, RJ, Brazil.

anisotropy of δ_i and δ_m values in steels.

The objective of the present work is to investigate the effect of side grooves on testpieces on values of COD at initiation and on the dispersion of COD values of a high strength low alloy atmospheric corrosion resistant steel. The influence of two testpiece orientations on those values was also investigated.

MATERIAL AND EXPERIMENTAL METHODS

The chemical composition of the steel studied is (wt%): 0.14 C, 0.92 Mn, 0.010 P, 0.030 S, 0.27 Si, 0.25 Cu, 0.57 Cr, 0.22 Ni and 0.039 Nb. Its tensile properties are: σ_y = 426 MPa, σ_u = 570 MPa and elongation in 50 mm = 30.6%. The COD testpieces were machined from 27 mm thick hot rolled plates, with square sections of 20 x x 20 mm (geometry G1). 45° V shaped side grooves, 4 mm deep, were machined on some testpieces in such way that the tip of the grooves should coincide with the fatigue pre-cracks (geometry G2). Figure 1 shows the two testpiece orientations used.

Four point bending was used for both fatigue pre-cracking and COD tests. The top load span was 80 mm and the botton one was 40 mm. The fatigue pre-crack nominal lengths were 6 mm and they were grown in a 10 ton Amsler fatigue machine. The COD tests were performed in a 10 ton Instron screw driven testing machine, using an Instron clip-gauge for assessing the crack opening displacements. The knife edge heights were 6 mm.

RESULTS

Three main types of load (P) versus clip-gauge displacement (V) curves were obtained, as illustrated by Figure 2. Also in Figure 2 are the criteria used for obtaining the critical values of V (V_c). Values of COD were calculated using the expression (12):

$$\delta = 0.4336\, V + 9.1 \times 10^{-4} \qquad (1)$$

were δ and V are given in millimetres. Table 1 shows the results obtained.

The results show that there was always a relationship between the type of test record and the fracture mode, as follows: the record of Figure 2(a) corresponds to cleavage fracture; the one of Figure 2(b) corresponds to a transition of fracture mode from ductile to cleavage while delamination occurred in Figure 2(c). In this case, one testpiece (B7) also showed a transition of fracture mode. Delamination corresponds to ductile crack growth which deviates,after some growth to a plane normal to the previous one. Testpieces showing this behaviour did not fracture during the tests.

Scanning electron microscopy was used for a fractographic analysis. It showed that the testpieces always presented well defined stretched zones, even the ones presenting cleavage fracture. A metallographic analysis was also made. Unetched samples showed elongated inclusions, typical of rolled plates where control of inclusion morphology was not done. The etched samples showed a ferritic-pearlitic microstructure. A metallographic anal ysis of testpiece planes normal to the fracture surfaces and close to them revealed that the delamination was caused by the inclusions. In this case, crack propagation deviates from the original routes after some growth following then a path dictated by the elongated inclusions, as illustrated in Figure 3. A detailed fractographic and metallographic analysis of the steel of the study is presented in other work (13).

TABLE 1 – Experimental Results

Orientations	Geometry	Testpiece	Record	Fractography	a (mm)	V_c (mm)	δ_c (mm)
LT	G1	A5	2a	cleav.	6.6	0.310	0.134
LT	G1	A7	2a	cleav.	6.4	0.300	0.129
LT	G1	A8	2c	delam.	7.0	1.240	0.531
LT	G1	A9	2c	delam.	6.5	1.265	0.541
LT	G1	A10	2c	delam.	7.1	1.450	0.620
LT	G1	A17	2a	cleav.	6.9	0.355	0.153
LT	G1	A21	2c	delam.	6.7	1.470	0.629
LT	G1	A33	2a	cleav.	6.2	0.395	0.170
LT	G2	A15	2b	trans.	6.9	0.570	0.245
LT	G2	A20	2a	cleav.	6.6	0.320	0.138
LT	G2	A24	2a	cleav.	6.9	0.275	0.119
LT	G2	A34	2b	trans.	5.7	0.745	0.319
LT	G2	A36	2b	trans.	6.2	0.760	0.326
LV	G1	B2	2b	trans.	5.7	0.610	0.262
LV	G1	B5	2a	cleav.	6.4	0.370	0.159
LV	G1	B6	2b	trans.	6.2	1.145	0.490
LV	G1	B9	2b	trans.	6.4	0.765	0.328
LV	G2	B1	2a	cleav.	5.2	0.300	0.129
LV	G2	B7	2c	trans.	6.1	0.765	0.328

DISCUSSION

Table 2 shows the mean COD values ($\overline{\delta}$) their standard deviations (s) and dispersions ($s/\overline{\delta}$) for the orientations and geometries studied (rows 1, 4, 7 and 10). Also shown in the table are the fracture modes: cleavage, which gives values of COD at initiation, and ductile crack initiation which corresponds to fully crack growth, giving COD at maximum load values, or also to a transition of fracture mode from ductile to cleavage, during the tests.

Dispersion of Results

The values of $s/\overline{\delta}$ from rows 1, 4, 7 and 10 show that the dispersion of results is high, about 50%. On the other hand, grouping the results following their fracture mode or the type of test record obtained, which is related to the fracture mode, resulted in a marked decrease of the dispersion (compare rows 2 and 3 with 1, 5 and 6 with 4 and 9 with 7). From this, it appears that each group presents its own statistical distribution. These observations, together with the results of Johnston (3), seem to indicate that the COD values follow a bimodal distribution resulting from the ductile and cleavage contributions to the fracture behaviour of the steel in the transition region.

TABLE 2 – Mean values, standard deviations and dispersions of various groups of results

Row	Orientations	Geometry	Fracture behaviour	$\bar{\delta}$ (mm)	s (mm)	s/$\bar{\delta}$ (%)	Row
1	LT	G1	all	0.363	0.235	65	1
2	LT	G1	cleav.	0.147	0.019	13	2
3	LT	G1	duct.	0.580	0.051	9	3
4	LT	G2	all	0.229	0.098	43	4
5	LT	G2	cleav.	0.129	0.013	11	5
6	LT	G2	duct.	0.297	0.045	15	6
7	LV	G1	all	0.310	0.139	45	7
8	LV	G1	cleav.	0.159	–	–	8
9	LV	G1	duct.	0.360	0.117	33	9
10	LV	G2	all	0.229	0.141	62	10
11	LV	G2	cleav.	0.129	–	–	11
12	LV	G2	duct.	0.328	–	–	12

Effect of testpiece orientation

Two effects can be separated here: on δ_i and on δ_m. δ_i was not much affected by the orientations studied (compare, in Table 2, the values of $\bar{\delta}$ of rows 2 and 8 and also of 5 and 11). On the other hand, δ_m for geometry G1 changes substantially with the change of orientation (rows 3 and 9), as opposed to geometry G2 where it remained almost unchanged (rows 6 and 12). This results from the delamination taking place in orientation LT of G1 which is avoided by the side-grooves of geometry G2, as discussed in next section.

Hertzberg (14) presented a model which can explain the delamination showed by some testpieces of the present work. The fatigue crack front is, for orientation LT, normal to the largest dimension of the inclusions and paralel to the intermediate one. With testpiece loading and decohesion at the inclusion/matrix interfaces, their distribution is such to allow the principal stress on planes paralel to the rolling surfaces to decrease to low values. As a consequence, there is a relaxation of stress triaxiality and a directional increase of fracture toughness normal to the rolling surface. The crack, which is growing on a plane normal to the rolling surface, finds stronger opposition to grow on that plane and less opposition on a plane paralel to the rolling surface. Thus it is easy for it to blunt, deviating from the initial growth plane and producing delamination.

Orientation LV is such that the fatigue crack front is also normal to the largest dimension of the inclusions but paralel to the smallest one. Delamination does not occur in this case since it is easier for the crack to propagate from the beginning on ou a plane normal to the rolling surfaces. Crack blunting is much more difficult in this case with the result that the crack does not deviate from the initial growth plane.

Effect of side grooves

The side grooves, as already shown, avoided delamination.

This may have resulted more from a geometrical effect of the grooves directing crack growth than from a substantial increase of stress triaxiality. This behaviour is discussed more deeply in other work (13). As a consequence of the grooves, the testpieces did not show delamination, presenting instead a change of fracture mode from ductile to cleavage,during the test. A transition of fracture mode was also found by Bastian and Charles (15) which explained it as follows: with ductile crack initiation, fracture takes place at a local stress level lower than the cleavage stress of the material. With this ductile crack growth and resulting stress intensification, the cleavage stress level of the material can be reached, causing therefore a change of fracture mode from ductile to cleavage.

Here also it is necessary to separate the effect of the side grooves on δ_i and on δ_m. δ_i was little affected by the grooves (values of $\overline{\delta}_i$, rows 2 and 5 and 8 and 11, Table 2). This could result from the fact that the stress triaxiality at the tip of the crack, without the grooves, was already enough to produce the minimum value of COD or, even, that the grooves did not effectively increase the stress triaxiality. In relation to δ_m, orientation LV (rows 9 and 12) showed little change as a result of the introduction of the side grooves, reinforcing the hypothesis that the grooves used were not efficient stress concentrators. On the other hand, the values of δ_m for LT orientation decreased (rows 3 and 6), because delamination was avoided in this case.

It can be seen from the values of $\overline{\delta}$, rows 2 and 4 and 8 and 10 of Table 2, that the side grooves were not able to produce values of δ_i from a single testpiece, as proposed by some authors (8, 9). Our results show that removing the side ligaments by side grooving is not enough to produce a coincidence of δ_m with δ_i. It appears that an extra stress concentration is necessary in order to obtain such a coincidence. From our results it seems that further research on the effect of side grooves on COD is therefore recommended.

CONCLUSIONS

The dispersion of the experimental values of COD is high. The statistical distribution of results appears to be bimodal, with cleavage and ductile components.

The LT and LV testpiece orientations do not affect the values of COD at initiation.

The values of COD at maximum load are influenced by the orientation of the testpiece. Testpieces of LT orientation showed delamination and larger values of COD at maximum load than the ones of LV orientation.

Side grooves on the COD testpieces did avoid delamination to take place, decreasing therefore the values of COD at maximum load for LT orientation. In the case of LV orientation, which did not present delamination, COD at maximum load did not change with the side grooves.

The side grooves did not affect substantially the values of

COD at initiation.

The introduction of side grooves did not assure the coincidence of COD at maximum load with COD at initiation and, therefore, obtaining COD at initiation with a single testpiece.

SYMBOLS USED

COD = crack opening displacement
δ = COD value
δ_i = COD at initiation
δ_m = COD at maximum load
$\bar{\delta}$ = mean COD value
σ_y = yield stress
σ_u = ultimate tensile stress
P = load
P_{max} = maximum load
s = standard deviation
V = clip-gauge displacement
V_c = critical clip-gauge displacement

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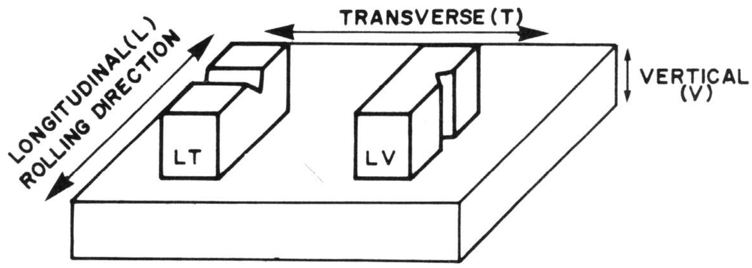

Figure 1 Testpiece orientations

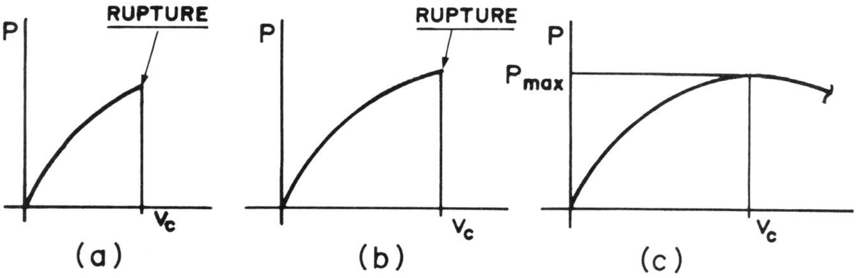

Figure 2 Types of test records obtained

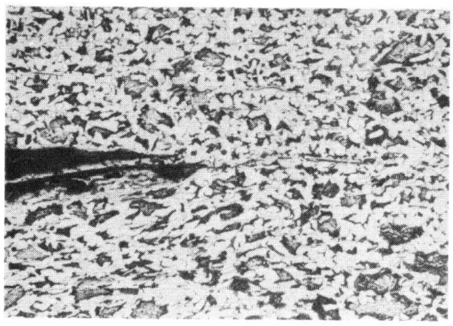

Figure 3 Optical micrograph close to the fracture surface of a testpiece with delamination. Its front is directed to an inclusion (Nital 2)