EXPERIMENTAL STUDIES OF STABLE CRACK GROWTH

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ABSTRACT

In this study the tearing modulus and the toughness J_{Ic} were determined for two structural steels. Different types of specimens and different methods of crack growth measurement were used. The experiments were modelled in FEM-calculations using a two-dimensional model.

KEYWORDS

Tearing modulus; J_{Ic}-toughness; compliance technique; heat tinting; stable crack growth.

INTRODUCTION

The tearing modulus has been proposed as a relevant parameter for treating stable crack growth in ductile materials (Paris and co-workers, 1979). Experimental determinations of the tearing modulus in different steels have been done by several investigators as reported in P.C. Paris (Ed.) CSNI Report No. 39. Procedures for application of the tearing modulus to different structures have also been worked out (see the same report).

In the present paper different methods for determination of the tearing modulus are compared. Two steels are studied and two different laboratories have taken part in the investigation.

MATERIALS

The two steels studied are one quenched and tempered steel OX 812E and another structural steel OX 540, both delivered by the Oxelösund Steel Works. The steels are in plate form (thickness 20 mm) and the specimens are cut with the crack oriented perpendicular to the rolling direction.

The mechanical data and the composition of the materials are given in Tables 1 and 2.

TABLE 1 Material properties

	$R_{0.2\%}$ MPa	R_B MPa	δ_5 %	E GPa
OX 812E	680	720	22.5	210
OX 540	420	570	33	210

TABLE 2 Material composition

	C %	Si %	Mn %	Cr %	Ni %	Mo %	P %	S %	V %	Nb %
OX 812E	0.10	0.31	1.17	<0.05	<0.05	<0.05	0.014	0.002	0.06	
OX 540	<0.2	0.15-0.5	1.8				0.035	0.035		0.05

SPECIMENS

In the tests compact tension (CT) and three point bend (TPB) specimens were used. The specimens were made according to the ASTM norm E399 (1974) with reduced thickness B = 20 mm and with W = 40, 50 and 100 mm for the CT-specimens and 40 and 50 mm for the TPB-specimens. For CT-specimens used in the compliance-technique tests the loading pin holes had the diameter increased with 2 mm compared to the norm to decrease elastic bending. Some of the specimens were side grooved.

TESTING PROCEDURE

For determination of crack length one laboratory used the heat tinting method in the form it is recommended by the ASTM task group for J_{Ic} measurement. For determination of one experimental J = J(Δa) curve five to twenty tests were made with crack growth between zero and two millimeter in each test.

The other laboratory used the compliance technique with 10-20% unloading after roughly each 0.5 mm of load point displacement. The crack-opening displacement was measured and recorded against load. Well-known relations between load and crack opening were used (Tada and co-workers, 1973, Hudah and co-workers, 1978) to determine crack length from the measurements. The method was checked through measurements on specimens with fatigue cracks and found to give very correct results. To increase the sensitivity of the method the change in compliance was measured and electrically amplified.

The initial crack was obtained through fatiguing the specimen. It had a straight front. After stable growth the crack front had thumbnail form with almost no growth at the surface.

For the heat tinting method crack length was defined as cracked area divided by specimen thickness, i.e. as an average length. For the compliance technique the crack length found by the evaluation procedure described above is reported here uncorrected. This is thus the length of a straight crack in a specimen with the same compliance as the thumbnail cracked specimen.

Thus different definitions of crack length are used in the two methods. This is one obvious reason for deviations between the results.

In all experiments J was updated with respect to crack length increase during the test. For calculation of J the well-known one specimen formula was used for the TPB-specimens and the Merkle-Corten (1974) formula for the CT-specimens.

For the J-integral calculations load-point displacement for the CT-specimen was measured between points on the specimen on each side of the crack along the loading line. This displacement differed significantly from displacement measured between the loading pins.

VALIDITY CONDITIONS

The conditions for J-controlled crack growth are given by Paris and co-workers (1979). They are for CT- and bend specimens

$$\omega = \frac{dJ}{da}\,\frac{c}{J} \geq 10 \tag{1}$$

$$\Delta a < 0.06\ c \tag{2}$$

$$c > 25\,\frac{J}{\sigma_o} \tag{3}$$

and

$$B \geq c\ . \tag{4}$$

Here c is ligament width and B specimen thickness. Δa is crack growth.

Of these conditions eq. (4) was not satisfied in the large (W = 100 mm) specimens, whereas the more basic condition, eq. (3), is satisfied except in some cases at large Δa. The ω parameter is listed in the table for the different tests.

TEST RESULTS

The testing and the evaluation was computerized. J(a) was plotted against crack growth Δa for each specimen in the heat-tinting experiments and for each unloading in the compliance technique tests. A straight line was fitted to the test results to the right of the blunting line by the least squares method, Figs. 1 and 2. In the diagram the blunting line, the exclusion line and the line Δa = 0.06 c according to eq. (2) were drawn.

In OX 540 stable crack growth of the amount Δa = 0.1 c was measured. No significant change in dJ/da was observed at this value and points at this limit were included in the T-modulus calculations.

In the OX 812E specimens with W = 40 mm the tests are evaluated in some cases to crack growth up to Δa ≈ 0.15 c. There is no significant change in dJ/da above Δa = 0.06 c.

In Tables 3 and 4 all data are collected for the OX 540 and OX 812E materials, respectively. Figure 1 shows results from the heat-tinting experiments on seven OX 540 specimens with W = 100 mm. To study the influence of side grooving, grooved specimens were also used. It was found that for 15% side grooving both J_{Ic} and dJ/da decreased significantly whereas for 10% the effect was small. Figure 2 shows results from compliance-technique measurement on OX 812E specimens with W = 40 mm, without and with side grooves.

J_{Ic} is measured at the intersection of the blunting line and the dJ/da line.

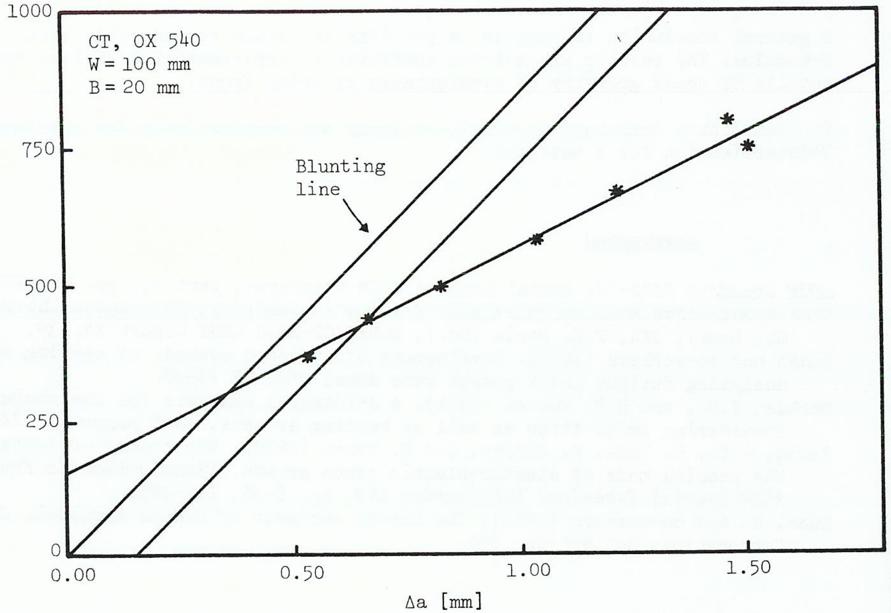

Fig. 1. Determination of stable crack growth with the best heat tinting method. Results from seven CT-specimens.

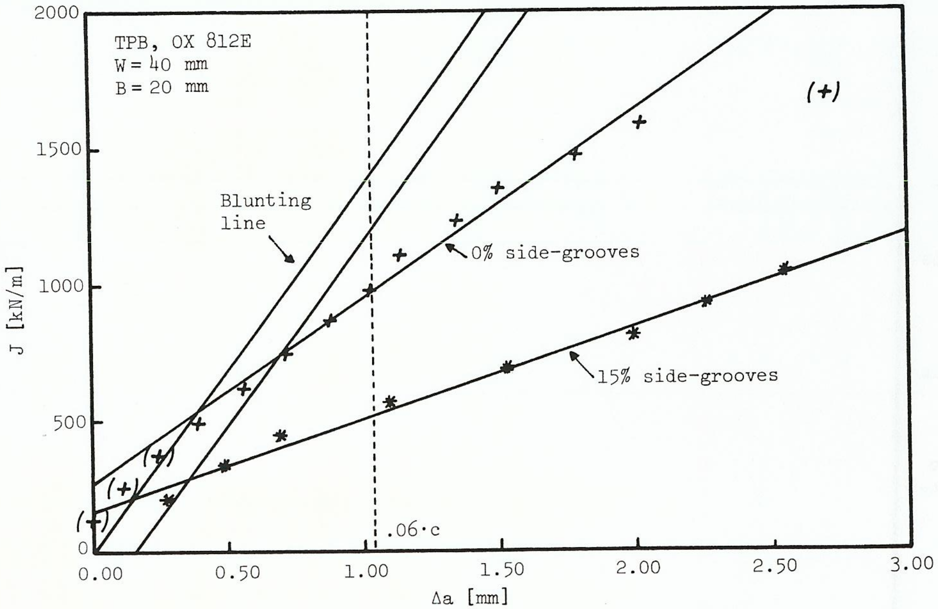

Fig. 2. Determination of stable crack growth using compliance technique. Results from two three-point bend specimens.

TABLE 3 Results for OX 540 specimens of thickness B = 20 mm

Specimen type/ Number of specimens	W mm	J_{Ic} kN/m	dJ/da MN/m^2	T	ω	Δa mm	Δa/c	Heat tinting/ Compliance
TPB/4	50	330	424	512	>20.3	1.0	<0.04	Heat tinting
CT/13	50	210	434	524	> 9.4	1.5	<0.06	-"-
CT/7	100	290	415	501	>14.7	1.5	<0.03	-"-
TPB/1	40	350	458	545	>11.4	1.3	<0.065	Compliance
TPB/1	40	328	540	647	>12.4	1.3	<0.065	-"-
TPB/1	40	397	434	517	>10.8	1.2	<0.06	-"-
TPBS/1*	40	250	343	408	>10.2	1.3	<0.065	-"-
CT/1	40	291	498	594	> 8.1	2.0	<0.10	-"-
CT/1	40	(608)	496	590	> 9.5	1.5	<0.075	-"-
CT/1	40	250	468	557	> 7.8	1.5	<0.075	-"-
CT/1	100	250	504	600	>20	2.0	<0.04	-"-

* 15% side grooves

TABLE 4 Results for OX 812E specimens of thickness B = 20 mm

Specimen type/ Number of specimens	W mm	J_{Ic} kN/m	dJ/da MN/m^2	T	ω	Δa mm	Δa/c	Heat tinting/ Compliance
TPB/6	50	420	666	302	>14.1	1.	<0.04	Heat tinting
CT/20	50	350	500	225	>11.0	1.5	<0.075	-"-
CT/13	100	360	612	278	>21.7	1.4	<0.03	-"-
TPB/1	40	608	648	292	> 6.8	2.0	<0.10	Compliance
TPB/1	40	505	600	270	> 8.2	1.5	<0.075	-"-
TPBS/1*	40	542	533	240	> 6.5	2.0	<0.10	-"-
TPBS/1**	40	264	389	175	> 5.2	3.0	<0.15	-"-
CT/1	40	500	548	247	> 5.5	2.5	<0.125	-"-
CT/1	40	635	535	241	> 7.8	2.4	<0.12	-"-
CT/1	100	611	467	210	>17.2	2.0	<0.04	-"-

* 10% side grooves, ** 15% side grooves

NUMERICALLY MODELLING OF CRACK GROWTH TEST

The tests have been simulated by node relaxation technique in FEM computations. The plasticity model employed was incremental v. Mises with variable strain hardening. The relaxation element was a one-dimensional truss with prescribed load-elongation properties closely approximating the unimaxial behaviour of the actual steel, up to the point of complete separation, thus including an instable portion where the load decreases with increasing elongation. In the numerical formulation, after instability point is reached the truss is decoupled and a force (iteratively computed) is applied to the appropriate node. When this force attains zero, separation is considered complete and the crack tip has advanced to the next (stable) truss. In practice, it is possible that several trusses are in the unstable region simultaneoulsy.

The finite element model was for cost reasons two-dimensional. The calculations were made for plane stress except for a small region at and in front of the crack tip where plane strain was prescribed. This was found to be necessary in order to get agreement with experimental results in the plastic range. Plane stress alone gave too low limit load and plane strain too high limit load. On the other hand the model used was too stiff in the elastic range, as is seen in Fig. 3 which shows the experimental and the calculated load elongation curves for a three point bend specimen; material OX 812E with stable crack growtn. The load-crack opening displacement curves show about the same agreement. The difference in elastic stiffness is easily corrected for.

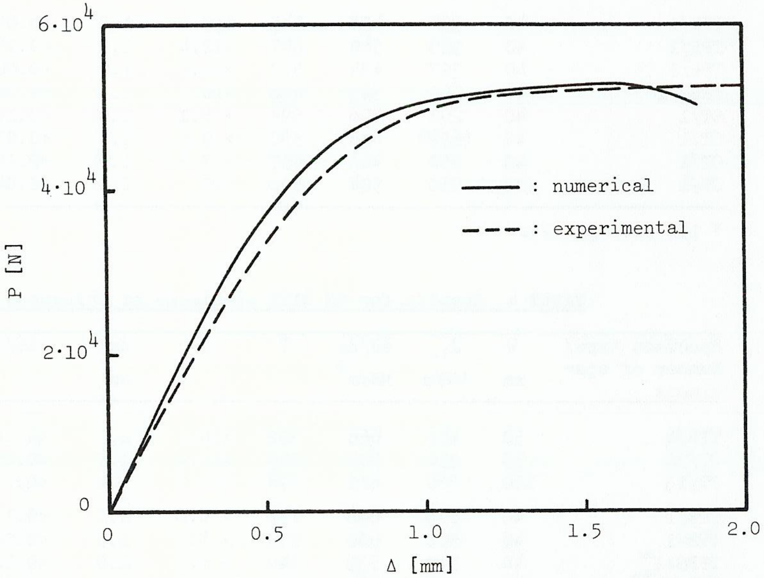

Fig. 3. Finite element and experimental load-displacement curves for three-point bend specimen with stable crack growth.

The J versus displacement curves agree almost exactly (<5% deviation). The T modulus for initial crack growth was evaluated to 370.

DISCUSSION

The materials that were used in the study have very high tearing modulus. This leads to great uncertainty in the determination of J_{Ic} with the procedure used in this case. This is because the slopes of the blunting line and the dJ/da-line do not differ very much. Although the amount of crack growth is measured and defined differently in the heat tinting and compliance tests the tearing modulus in the two cases does not differ significantly. For the steel OX 540 there is, however, a systematic deviation in T. This is probably due to the different definitions of amount of crack growth.

The condition eq. (2) is very restrictive and it seems to be necessary to allow larger values of Δa for it to be possible to construct the dJ/da-line accurately. From these tests it seems as if larger values were permissible.

A general conclusion is that it is possible to obtain reproducible results for the T-modulus. The results are not too sensitive to experimental technique and to details of crack geometry as straightness of crack front.

The compliance technique is simple to apply and requires only few specimens for T-determination for a material.

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