FRACTURE TOUGHNESS EVALUATION USING CIRCUMFERENTIALLY CRACKED CYLINDRICAL SPECIMENS

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In this study it was investigated whether a circumferentially cracked cylindrical specimen could be used for the determination of J_{Ic}. The ASTM E813 standard requires that relatively large specimens are used in order to provide sufficient constraint at the crack tip. Because a circumferentially cracked cylindrical specimen is smaller than the standard specimens, less material is needed for the test. The constraint at the crack tip is provided because the crack front does not reach the free surface of the specimen, as it does in the standard specimens. After precracking the fatigue ligament showed large amounts of eccentricity. Two types of eccentricity correction are used in this study. The first is applied to the crack extension, the second takes into account the bending stress caused by the eccentricity. Using both corrections, the spread between the specimens was reduced and the data points were close to those obtained with standard specimens.

INTRODUCTION

The aim of this study was to investigate whether a circumferentially cracked cylindrical specimen could be used for the determination of J_{Ic}.

The ASTM E813 standard requires that relatively large specimens are used for the determination of J_{Ic} and states minimum dimensions for the ligament and the thickness of the specimen. These requirements should ensure that sufficient constraint at the crack tip is provided. As the amount of material needed for the manufacture of the specimens according to the standard may not always be available, a smaller type of specimen is desired. As a circumferentially notched cylindrical specimen is smaller than the standard specimens, less material is needed for the test. Another advantage of this type of specimen is that manufacturing is quick and easy.

Although the specimen is small, sufficient constraint at the crack tip is provided because the crack front does not reach the free surface of the specimen, as it does in the standard specimens.

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EXPERIMENTAL PROCEDURE

The type of specimen used is a circumferentially notched cylindrical bar specimen and is displayed in figure 1. The material used was Fe 510 Nb. This steel was first hot-rolled to a thickness of 30 mm and subsequently normalised. This material complies with Fe E355 KT according to Euronorm 113-72. The mechanical properties of the material given by ten Horn (1) are:

Young's modulus: 211 GPa,
yield strength: 365MPa,
ultimate tensile strength: 540 MPa,
strain at maximum load: 0.175.

For this type of specimen the equation for J is given by Rice et al. (2) in equation (1).

$$J = \frac{1}{2\pi r^2}\left(3\int_0^{\delta_c} P d\delta_c - P\delta_c\right) \tag{1}$$

where r is the radius of the fatigue ligament, P is the applied force, δ_c is the load-line displacement due to the presence of the crack. Although δ_c cannot be measured directly, it can be calculated from the measured displacement, δ_m, using the following equation:

$$\delta_c = \delta_m - \delta_{sp} \tag{2}$$

where δ_{sp} is the displacement caused by the specimen and is estimated with equation (3).

$$\delta_{sp} = \frac{2P}{\pi E}\left(\frac{1}{r_0} - \frac{1}{R}\right)\tan(30°) + \frac{P}{\pi R^2 E}\left(L_g - 2(R - r_0)\tan(30°)\right) \tag{3}$$

where the right hand side contains the load-line displacements due to the conical and cylindrical part of the specimen over the gauge length, E is Young's modulus, r_0 is the radius of specimen at the root of the notch, R is the radius of the specimen's gross section, L_g is the gauge length.

A four-point rotating bending machine was used to precrack the specimens under constant load. As a consequence ΔK increases with crack growth and any eccentricity in the crack will become more pronounced as the crack grows. If the specimen is loaded using a constant displacement however, the ΔK drops as the crack grows. This means that any eccentricity in the crack would disappear as the crack grows. However constant displacement conditions could not be realised on our rotating-bending machine.

For the specimen types specified in the standard, the fatigue crack reaches the free surface of the specimen. In order to ensure that the specimen can provide enough constraint, requirements are stated in the standard for the thickness and the ligament of the specimen. The fatigue crack in the specimen used in this study does not reach the free surface of the specimen. As a consequence this type of specimen should be able to provide the required constraint. The study done by Giovanola et al. (3) showed that deep cracks provide more constraint than shallow cracks. For this reason deep fatigue cracks were chosen for this study. The deep cracks however do not comply with the standard as the ligament is too small. In order to investigate the possible precrack length dependence of the J_{Ic}, two different crack lengths were used, i.e. 1.5 mm and 1.0 mm. The definition of the crack length, a, is shown in figure 1.

After tensile loading, the specimens were heat tinted to mark the crack extension and subsequently broken at liquid nitrogen temperature. The crack surface was mapped using a microscope equipped with micrometer displacement gauges. With the measurement across the centre of the specimen, three corresponding points were measured: the edge of the machined notch, the fatigue crack tip and the tip of stable crack growth. In order to determine the eccentricity, ε, of the fatigue crack of a specimen the centre of gravity of the fatigue ligament was determined relative to the centre of the specimen. The centre of the specimen was assumed to be halfway between the left and right tip of the machined notch. The radius of the fatigue ligament was calculated relative to the centre of gravity. The difference in distance between the last two points and the centre of gravity provides the crack extension, Δa. These constructions can be seen in figure 2.

In order to correct for eccentricities, two eccentricity corrections were used:
A) correction for the crack extension
B) correction for bending forces

The eccentricity correction A comprises the use of the maximum instead of the average crack extension. Due to the eccentricity the applied loads shall mainly act on the part of the specimen where the fatigue precrack is the deepest. Therefore at this point the largest crack extension is expected. As a result the maximum crack extension should be used instead of the average crack extension when eccentricity occurs.

The eccentricity correction B corrects for the bending forces which occur due to the eccentricity. This correction is implemented by modifying the equation for the applied load as indicated in equation (4), where P_m is the measured force. A similar eccentricity correction for K_{Ic} was found by Ibrahim and Stark (4).

$$P = P_m + 2P_m \frac{\varepsilon}{R} \tag{4}$$

RESULTS

For most specimens the fatigue precrack was not concentric. Table 1 shows the eccentricity and radius of the fatigue ligament for the specimens.

Variations in diameter of the machined notch are found to affect the eccentricity. In figure 3a the effect of the standard deviation of the diameter of the machined notch on the eccentricity is shown. The presence of variations in the diameter of the machined notch will cause differences in ΔK and consequently lead to differences in crack growth rate during precracking.

Also an influence can be seen of the direction of the minimum diameter on the position of the centre of gravity of the fatigue ligament relative to the centre of the specimen. These two directions are approximately the same, as can be seen in figure 3b. Due to the measurement method only the diameter of the specimen could be measured and not the radius. Therefore the direction of minimum diameter, and direction of eccentricity were taken between 0 and 180°.

TABLE 1 - The Eccentricity and Average Radius of the Fatigue Ligament of the Specimens.

Specimen number	r_w (mm)	ε (mm)	Specimen number	r_w (mm)	ε (mm)
2	2.08	1.04	14	2.69	0.77
3	2.11	0.68	15	2.62	0.83
4	2.13	0.63	16	2.65	0.66
5	2.10	0.32	17	2.62	0.94
6	2.13	0.28	18	2.63	0.63
8	2.09	1.11	19	2.63	0.65
9	2.30	0.33			
10	2.05	1.52			
12	2.09	0.66			

The crack extension and J values for the specimens are shown in figure 4a. The effect of the use of both corrections can be seen in figure 4b.

On the same steel J tests were performed by Bholanath (5) using single edge notched bend (SENB) specimens. The results are shown in figure 4b. The specimen with the dimensions 270 x 60 x 28 mm complied with the ASTM standard. It can be seen from this figure that the points found with the cylindrical specimens are close to the points found with the SENB specimens.

In order to determine J_{Ic}, the standard specifies that a power law is fitted through the J-Δa data. The intersection between the power law and the 0.2 mm offset blunting line provides J_{Ic}. The standard gives equation (5) for the blunting line, while equation (6) is a more realistic the blunting line for this material given by Bholanath (5).

$$J = 2\sigma_0 \Delta a \tag{5}$$

$$J = 3.2\sigma_0 \Delta a \tag{6}$$

where σ_0 is the effective yield strength, i.e. the average of the yield strength and the ultimate tensile strength; Δa is the crack extension. In figure 4 equation (6) is used for the blunting line.

The J_{Ic} values were calculated using equation (6) for the blunting line and are shown in table 2. The table also shows the accuracy of fit, R^2, and the values as obtained for SENB specimens. It can be seen that by applying the both corrections the data points are

TABLE 2 - Calculated J_{Ic} values with Accuracy of Fit, R^2. Also J_{Ic} values from SENB Specimens, reference (5).

		J_{Ic} (N/mm)	R^2
No correction		421	0.29
Correction A		298	0.34
Correction B		812	0.59
Correction A and B		412	0.81
SENB	270 x 60 x 28 (mm)	488	
	140 x 30 x 15 (mm)	404	

better described by a power law than without the corrections.

DISCUSSION AND CONCLUSIONS

The fatigue precracking caused large eccentricities in the fatigue ligament. It is unlikely that the eccentricity is due to the rotating bending machine as the specimens were placed randomly orientated in the machine.

The variation in the diameter of the specimen correlates well to the eccentricities found in the specimens. This seems a plausible explanation. Any eccentricity in the machined notch could become larger as the crack grows. The fact that the direction of the eccentricity is approximately the same as the direction of the smallest diameter, is an indication that this is the most likely cause for the eccentricities. The specimens were therefore not made accurately enough for this purpose.

The two procedures for eccentricity correction seem to work reasonably well. It can be seen that the spread between the specimens is reduced. And the data points using both corrections are close to the data points obtained with SENB specimens.

The J_{Ic} value obtained with the cylindrical specimens is lower than the value obtained with SENB specimens that comply with the standard. This may be due to the fact that the range of the data points was small.

On the whole it is found that cylindrical specimens can be used for determination of J_{Ic} provided eccentricity corrections are applied.

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(5) R. Bholanath, "Bepaling van de scheurweerstandskromme van Fe-510Nb bij verschillende temperaturen", graduate report, Delft University of Technology, Faculty of Chemical Engineering and Materials Science, 1992.

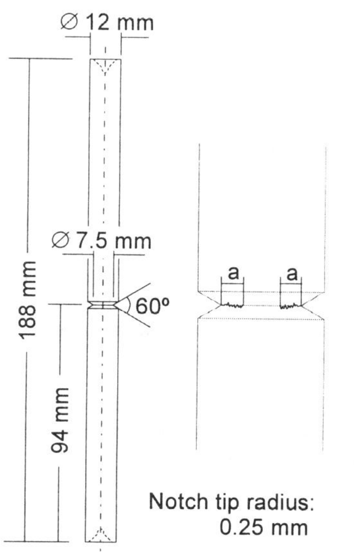

Figure 1. The specimen

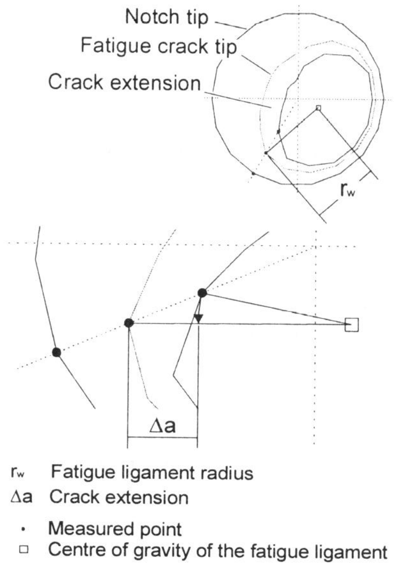

Figure 2. The determination of the radius of fatigue ligament and crack extension

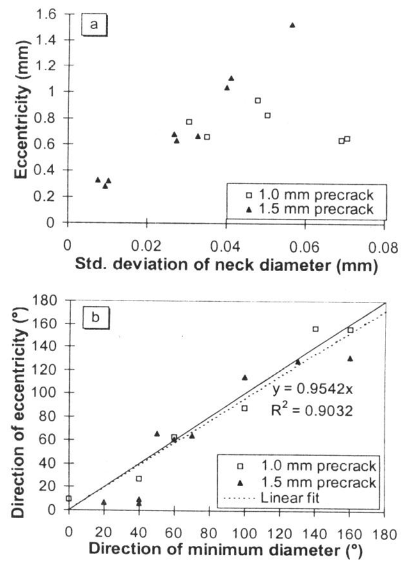

Figure 3. Influence of the variation of the diameter on the eccentricity

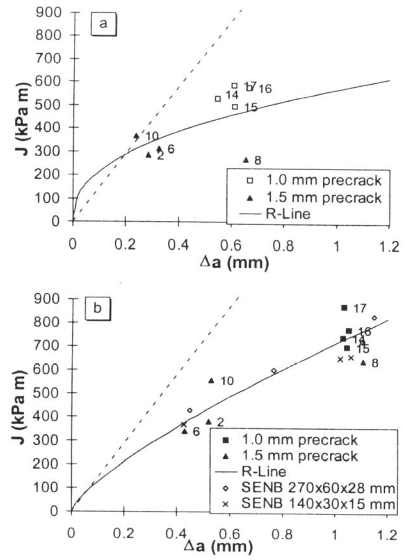

Figure 4. J-Δa plots without and with both eccentricity corrections