ESTIMATION OF STRESS TRIAXIALITY AHEAD OF A NOTCH BY MEANS OF VOID GROWTH STUDIES

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ABSTRACT

A procedure has been established to estimate the stress triaxiality ahead of a notch or crack using an experimental void growth law. Four variations of the Charpy specimen geometry (standard; pre-cracked; side grooved and side grooved and pre-cracked Charpy specimens) were tested in three point bending. The strain field and relative void volumes ahead of a notch or a crack were examined at the critical CTOD in these specimens. The results indicated that the fatigue crack and side grooves increase the triaxiality ahead of a notch or a crack. The increase in triaxiality observed is associated, however, with a reduced strain and strain gradient at fracture.

KEYWORDS

Ductile fracture; void growth; plastic strain; stress triaxiality; C-Mn structural steel

INTRODUCTION

In engineering design, a difficulty has always existed in that tests on small scale laboratory specimens cannot accurately predict the behaviour of large structures or machine parts; especially when two sizes differ by a wide margin. The size effect depends upon absolute dimensions and on the level of the yield stress for the material. These factors affect the constraints on yielding thus generating a stress triaxiality or hydrostatic component to the stress field. If equivalent hydrostatic components can be induced into small test pieces through geometrical factors then large scale behaviour could be predicted from small scale tests.

Despite the fact that many structures are designed on an elastic basis the presence of stress concentrators inevitably causes local yielding. Plastic flow may limit the high stresses which would be produced near the stress concentrator and thus a strain concentration may replace a stress concentration. In such cases, it is essential to ensure that the material has sufficient ductility to prevent failure in a ductile mode. Previous research indicates that the strain to initiate failure, the fracture strain, is strongly dependent on the stress state (Hancock, 1976; Ritchie, 1979). In order to predict the onset of ductile failure from an opening and blunting crack, it is necessary to understand the ductile behaviour of the material in a triaxial stress state. Theoretical and experimental studies into the micromechanisms of ductile fracture of materials have been reported (Beremin, 1981; McClintock, 1968; Rice, 1969; Shockey, 1980). The results of studies indicate that the stress state has a great influence on the micromechanisms of ductile fracture arising from the fact that a high stress triaxiality results in a much higher void growth rate with strain.

Bridgeman (1952) analysed the stress and strain distribution during ductile failure in the neck of a tensile specimen. This study indicated that the hydrostatic stress in the necked region of a tensile specimen has an effect on the ductility of the material. Although the Bridgeman analysis over-estimates both the effective plastic strain and the severity of the stress state at the centre of a notched tensile specimen, the analysis is adequate to show the trends in the stress state dependence of ductile fracture.

Recently, the finite element technique has been used to determine the stress and strain distribution in notched specimens (Imai, 1982; Kühne, 1982; Norris, 1979). (This has lead to more accurate determination of the severity of stress state.) The ASTM type A Charpy V-notch specimen represents a well-known specimen geometry. In the past, the specimen has been used in the impact loading mode as a quality control test for lower and intermediate strength grades of steel. The test is simple to perform and data are easy to analyse. However, the mechanics of the deformation process are difficult to analyse. It is worth noting that the CVN specimen is widely used in monitoring nuclear pressure vessels as the toughness diagonistic specimen. For the reactor pressure vessel surveillance, fracture specimens are periodically removed for testing during the life of the vessel. Therefore, the standard and modified CVN specimens have been studied for evaluating the fracture behaviour of the materials (Ritchie, 1978). Work related to standard Charpy specimens and therefore likely to be of general use.

The aim of the work reported below was to evaluate the stress triaxiality ahead of the notch or crack for different Charpy size specimens subjected to three point bending by using the void growth studies. In this work the strain field ahead of the notch or crack in CVN specimens and the influence of side grooves on increasing the thickness constraint has been investigated.

STRESS STATE AND VOID GROWTH MODEL

An effective stress $\bar{\sigma}$ in a complex stress system is calculated as follows:-

$$\bar{\sigma} = \frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{\frac{1}{2}} \qquad (1)$$

Where σ_1, σ_2 and $\sigma_3$are the principal stresses. The hydrostatic or the mean stress which causes volume change is

$$\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \qquad (2)$$

These two stress parameters may be combined into a single non-dimensional parameter $\sigma_m/\bar{\sigma}$ which is a measure of the severity of stress state or the stress triaxiality when $\bar{\sigma}$ is the effective stress for the onset of plastic flow.

The micromechanism of ductile fracture is nucleation, growth and coalescence of voids. In the C-Mn structural steel used in this work, voids mainly initiated at MnS, CaO and Al_2O_3 inclusions. The voids formed around the inclusions by decohesion of inclusions from the surrounding metal matrix.

After nucleation, voids grew under the influence of plastic strain and stress triaxiality. The Rice and Tracey model (1969) quantifies the average radius change dR at any instantaneous radius R with plastic strain increment ε^P and stress triaxiality $\sigma_m/\bar{\sigma}$ as follows:

$$\frac{dR}{R} = 0.558 * d\varepsilon^P * \sinh\left(\frac{3}{2}\frac{\sigma_m}{\bar{\sigma}}\right) \qquad (3)$$

This model for void growth was derived for a single void in a semi-infinite, ideally plastic material. Shockey and colleagues (1980) suggested a modified form of equation 3 for a work hardening material and proved its validity over a small range of stress triaxiality. The simplified model is:

$$V_v = V_o \exp\left[T_i * (\varepsilon^P - \varepsilon_o^P) * \frac{\sigma_m}{\bar{\sigma}}\right] \qquad (4)$$

Here V_v and V_o are the relative void volumes at plastic strains of ε^P and ε_o^P respectively, ε_o^P being the plastic strain at the nucleation of voids. Experiments conducted by Shi (1982) showed that the void growth observed at much higher triaxiality of 4.13 also obeys equation 4. For BS4360 50D structural steel, various constants in equation 4 were found to be as follows $\varepsilon_o^P = 0.002$, $V_o = 0.0018$ and $T_i = 5.68$ (Barnby, 1982). This void growth coefficient T_i was obtained from the specimens, in which the stress triaxiality changed from 0.33 (the effective factor for a tensile bar (Rice, 1969) to 4.13 (the factor for a plane strain crack (McMeeking, 1977)). The void growth coefficient, therefore, describes behaviour over a wide range of constraints.

EXPERIMENTAL PROCEDURE

The specimens were made from a 51 mm thick plate of a normalized BS 4360 50D structural steel. The chemical composition is as follows (wt)%.

TABLE 1 Chemical Composition of the Steel

C	Mn	Si	S	P	Al	Cu	Ni	Cr
0.18	1.42	0.23	0.008	0.007	0.03	0.11	0.25	0.21

Mo	Co	Sn	V	Nb	Fe
0.03	0.01	0.008	0.006	0.006	Balance

The standard CVN specimen conformed to ASTM E23 type A. The specimen orientation was L-T with respect to the rolling direction of the plate. The side grooves were machined to following geometry: (a) root radius 0.25 mm (b) included angle 45° (c) varying depth from 0 at the notch root to a maximum of 3 mm at the back face of the CVN specimen. A set of standard and side grooved specimens were fatigue cracked to a/w ratio of 0.5.

The specimens were tested at room temperature in three-point bending using a 50 KN Instron testing machine at a cross head displacement rate of 0.02 cm/min. Prior to the test, the side faces of the specimens were polished and micro-hardness indentations were made on either side of the notch, or the crack plane, to act as gauge lengths. During the test, photographs were periodically taken to monitor the changes in notch or crack geometry and the change in the gauge lengths. Ductile fracture initiation was determined by means of the electrical potential drop technique and the CTOD for initiation of cracking was recorded photographically. The specimens were subsequently unloaded and sectioned in liquid nitrogen in a plane perpendicular to the crack plane in order to measure the relative void volumes ahead of the crack tip at the ductile crack initiation event. The measurements were made by observing the fracture surfaces on a scanning electron microscope. A statistical point counting technique was used to estimate the relative void volume.

RESULTS AND DISCUSSION

The shear strains ahead of notch or crack were derived using $0.5 * \ln (l_f/l_o)$, where l_f = final distance between the marks, l_o = initial distance between the marks. These are presented in Figs. 1 (a) to 1 (d).

Comparison of Figs. 1 (a), 1 (b) and 1 (c) shows that the fatigue crack and side grooves both reduce the strains and the strain gradients observed in the standard CVN specimen. Figure 2 shows a comparison of the shear strain fields observed in the different types of specimens at ductile crack initiation (at the critical CTOD). The strain distributions ahead of the notch or the crack tip are dependent on the geometry. The side grooves reduce the strain gradient. Comparison of strains at the notch and at crack tips shows that the notch tip shear strain is about 3.3 times the shear strain at the crack tip. The CTOD value for notched specimens was found to be 4.5 times the CTOD observed in fatigue cracked CVN specimens. This is consistent with the previous observations that the critical CTOD value is dependent on the constraint at the crack or the notch tip. An increase in constraint or the stress triaxiality reduces the critical CTOD (Knott, 1973).

The present studies were instigated to evaluate the stress triaxiality ahead of the notch in the Charpy size specimens by using the void growth law. The maximum void growth and by implication triaxiality is generated at a specific distance ahead of the notch or the crack tip. The finite element analysis of the standard CVN specimen indicated that the maximum value of the stress triaxiality should develop at about 0.5 mm ahead of the notch root (Norris, 1979). In the present study a region between 0.4 mm and 0.5 mm ahead of the notch tip was chosen to investigate the void growth. Figure 3 shows a typical scanning electron microphotograph of voids observed.

The point counting to obtain void volumes was carried out directly on the screen of a scanning electron microscope. The relative void volume for each specimen is an average of 100 random measurements. The results of point counting at 0.5 mm ahead of the notch or the crack tip are given in the following table. The triaxiality values in the table are calculated using equation 4 with T_i determined from the Rice and Tracey (1969) effective triaxiality for a tensile bar and the McMeeking (1977) value for a crack.

The void growth results indicate that a fatigue crack has a higher triaxiality compared with the constraint generated by side grooves in a notched specimen. Higher strains and strain gradients are also observed in notched and side grooved specimens. This arises from the smaller constraint in the specimen which necessitates higher strains in the near notch tip region at fracture. Higher constraints are generated in the fatigue cracked specimens which leads to lower strains and strain gradients in the region ahead of the crack tip. The deformation is more localised to the notch tip, though the strains and strain gradients very close to the tip could not be measured. However, the experiments are sufficiently accurate to estimate strains at 0.5 mm ahead of the crack tip. If the stress ahead of the crack or the notch tip and the fracture behaviour in a small scale specimen is identical to those in large structure then the inexpensive pre-cracked, side grooved CVN specimen might offer considerable promise to quantify the failure analysis.

TABLE 2 Experimentally determined shear strains, relative void volumes ahead of crack/notch tip and stress triaxiality

Specimen Type	Specimen No.	Plastic Shear Strain ε^P	Relative Void Volume V_v	Stress Triaxiality $\sigma_m/\bar{\sigma}$
Standard CVN	B1T	0.145	0.00313	0.68
	B2T	0.126	0.00275	0.60
Side grooved CVN	S7T	0.215	0.00463	0.78
	S8T	0.190	0.00438	0.83
Fatigue-cracked CVN	B19V	0.063	0.00538	3.16
	B23V	0.067	0.00425	2.63
Fatigue-cracked Side grooved CVN	S13V	0.072	0.01013	4.13*
	S19V	0.076	0.00888	4.13*

* Values predicted by McMeeking (1977)

CONCLUSIONS

1. Experimental void growth studies may be used to estimate the stress triaxiality ahead of the notch or the crack in CVN specimens with reasonable accuracy assuming that the "known" calibration points for triaxiality are correct.

2. Side grooves and fatigue cracks were found to enhance the stress triaxiality in the Charpy sized specimens.

3. The notch or crack tip strains and the strain gradients determined experimentally were found to decrease with increase in constraint.

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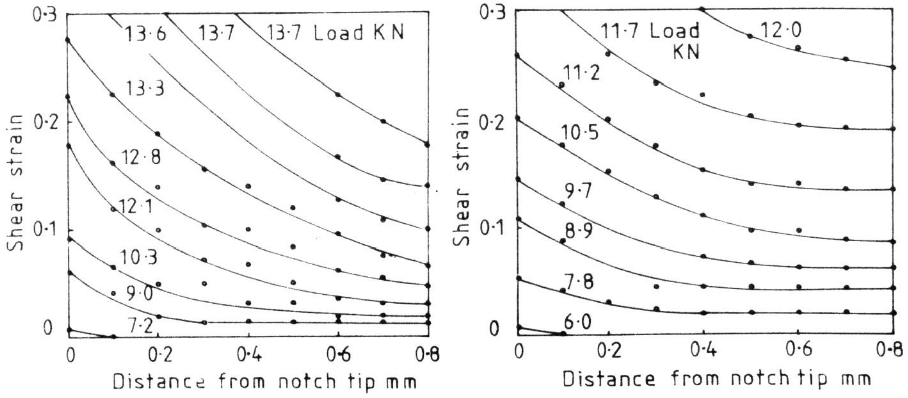
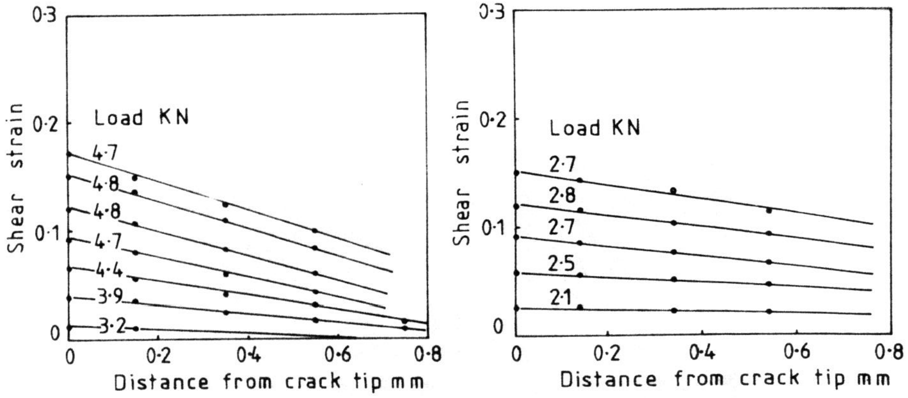


(a) Standard CVN specimen

(b) Side-grooved CVN specimen



(c) Pre-cracked CVN specimen

(d) Pre-cracked side-grooved CVN specimen

Fig. 1. Variation of the shear strain fields (derived from the extensional strain normal to the plane of cracking) ahead of the notches for Charpy size specimens

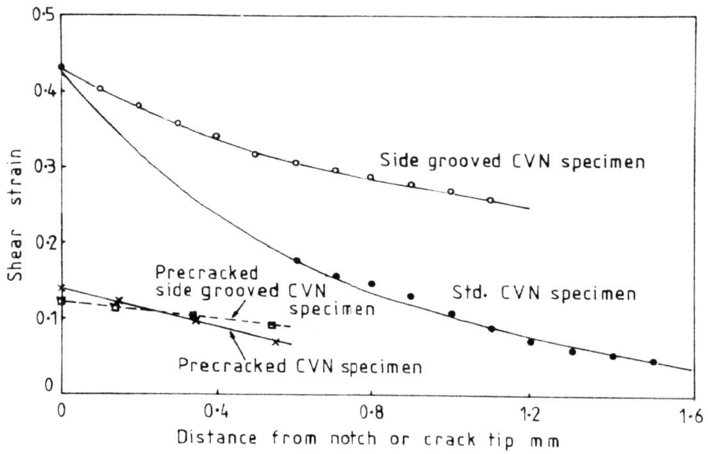


Fig. 2. The shear strain fields at maximum load for Charpy size specimens

Fig. 3. Typical SEM photograph of the voids observed (side-grooved CVN specimen loaded to crack initiation CTOD)