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EXPERIMENTAL STUDY ON THE EFFECT OF PLASTIC CONSTRAINT ON DUCTIAL TEARING

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ABSTRACT

The effect of plastic constraint on the initiation of ductile tears in four different alloy steels has been experimentally studied by measuring the crack opening displacement and J-integral at initiation in three-point bend specimens with deep and shallow notches in this paper. Experimental results of seven groups of different strength alloy steels show that both ì and Jì values of ductile tear from the shallow crack specimens which have less constraint flow field are significantly higher than deeply notched specimens. Slip-line- field analysis shows that, for shallow crack, the hydrostatic stress is lower than that from standard deeply cracked bend specimen, which develops a high level of crack tip constraint, provides a lower bound estimate of toughness, will ensure an unduly conservative approach when applied to structural defects, especially if initiation values of COD and J-integral are used.

KEYWORDS:

Ductile tearing, plastic constraint, slip line field, toughness, COD, J-integral

INTRODUCTION

Crack Opening Displacement (COD) and J-integral concepts of fracture are the accepted methods of estimating the significance of a crack or defect in structural steels. In design practice, the critical value at initiation $_i$ and J_i , are normally measured on three-point-bend specimens where the crack depth is approximately half the depth of the beam and the plastic flow is confined to the ligament. Since the plastic flow is constrained, the hydrostatic component of stress in these specimens is high. However, in practice many defects are shallow and the plastic flow associated with them reaches the surface of the component. In this case, the hydrostatic component of stress is smaller and the constraint is lower. As a consequence, the assessment for many shallow defects, the normal method is unduly conservative.

Experimental and theoretical study on the effect of the ratio of notch depth to specimen depth (a/w) on $_i$ and J_i is therefore necessary. Although many previous work have pointed out that shallow crack specimens give markedly higher values of $_i$ and J_i than deeply notched specimens [1-6], someone still doubt the correctness of it. In this paper, we examine the effect of shallow notches on ductile tearing in four Chinese alloy steels.

MATERIALS AND TESTING

Materials and Specimens

Steel 17CrNi4 was heat-treated to three different strength levels. Their mechanical properties are given in Table 1. Another alloy 18CrNiWA was heat-treated into two groups of different strength. The Properties are given in Table 2. The properties of steel 40Cr are given in Table 3. The properties of a structural steel are given in Table 4. Test specimens are of B=12.5mm, W=25mm, S=4W. The deep notch specimens are with a/W=0.5 and the shallow with a/W=0.1 or 0.2.

Experimental Procedure

Fatigue cracks were produced in all the specimens before they were tested. The toughness tests were carried out on a MTS-810 testing machine of 250 KN. Two clip gauges were used. One was to measure the crack mouth displacement V, the other was to measure the load-point displacement , P-V and P- plots were simultaneously recorded on an X-Y-Y recorder. After off-loading, specimen crack fronts were marked by heat tinting or re-fatigue. Then specimens were broken at low temperature. Crack length and crack extension a were measured with an optical micrometer with 0.001 mm per division and according to the seven-point average procedure. All tests were made at room temperature.

TABLE 1
MECHANICAL PROPERTIES OF STEEL 17CrNi4

Steel	group A	group B	group C
Yield strength(MPa)	932	864	736
Ultimate strength(MPa)	988	939	841
Work-hardening exponent n	0.051	0.057	0.068

TABLE 2
MECHANICAL PROPERTIES OF ALLOY 18CrNiWA

Group	A	B
Yield strength(MPa)	1045	1099
Ultimate strength(MPa)	1257	1415
Elongation	18.6	16.5

TABLE 3
MECHANICAL PROPERTIES OF STEEL 40Cr

Yield strength(MPa)	1043
Ultimate strength(MPa)	1252
Elongation(%)	12.5

For shallow crack specimens, the plastic flow spreads to the surface of the beam and the COD cannot be accurately obtained from a clip gage measurement at the mouth of a crack. Therefore, a replication technique was used. The values were measured by infiltrating the crack with a catalytically hardening silicone rubber Unitek Xantropren Blue dental impression material[1].

TABLE 4
COMPOSITIONS AND MECHANICAL PROPERTIES
OF THE STRUCTURAL STEEL

(a) Chemical analysis

C	Mn	Si	P	S
0.100	0.460	0.300	0.010	0.014

(b) Mechanical property

Ultimate strength(MPa)	1045
Yield strength(MPa)	715
Elongation to break(%)	19.20
Hardening exponent n	6.80

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental results of three groups of different strength alloy steel 17CrNi4 are shown in Figure 1 and 2. Results of two groups of different strength steel 18CrNiWA are shown in Table 5. Results of COD and J-integral of alloy 40Cr with a/w=0.5 and a/w=0.1 are shown in Figure 3 and 4 respectively. Results of the structural steel are shown in Table 6.

All the results show that both $_i$ and J_i values of ductile tear from the shallow notches (a/w=0.1) are significantly higher than deeply notched specimens. As we have already seen in our previous works [3,4], the reason is that the plastic flow spreads to the top surface of the specimen and lead to a decrease in plastic constraint and stress triaxiality at the crack tip.

TABLE 5
RESULTS OF ALLOY 18CrNiWA

Group	$_y$(MPa)	*a/w*	J_i(MN/m)	$_i$(mm)
A	1045	0.5	0.0644	0.037
		0.1	0.0883	0.059
B	1099	0.5	0.0853	0.046
		0.1	0.1022	0.066

TABLE 6
RESULTS OF THE STRUCTURAL STEEL

a/w	J_i(MN/m)	$_i$(mm)
0.1	0.0921	0.093
0.2	0.0750	0.078
0.5	0.0582	0.065

The hydrostatic stresses for shallow cracks are smaller than for deeper cracks. Figure 5 shows a slip-line field in a three-point bend specimen containing a short crack. At the crack tip, the hydrostatic stress is given by:

$$s_H = 2kb + kp/2 - k(1 - 4w) \quad (1)$$

with decreasing a/W, the angle increased and the angle slightly decreased, the hydrostatic stress $_H$ therefore decreased. It explains the results that $_i$ and J_i values of shallow crack specimens are higher than those of deep ones. As a consequence, the assessment of the significance of many shallow defects by the normal method is unduly conservative.

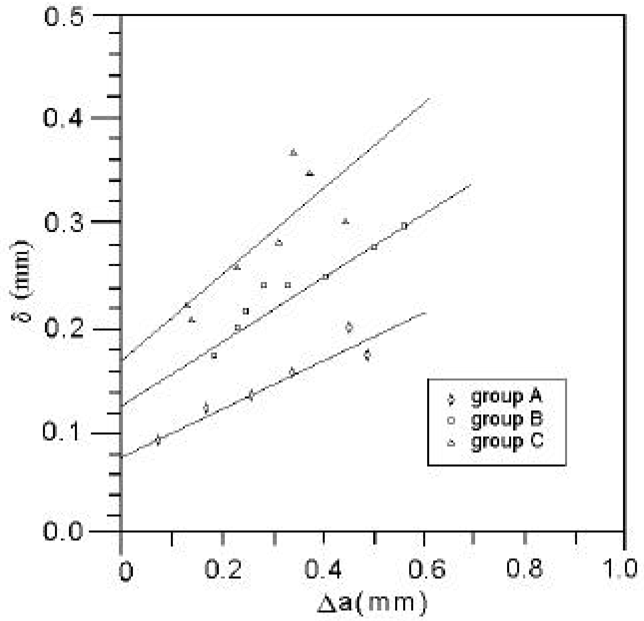

Figure 1: vs a of three groups of steel 17CrNi4 with a/w=0.5

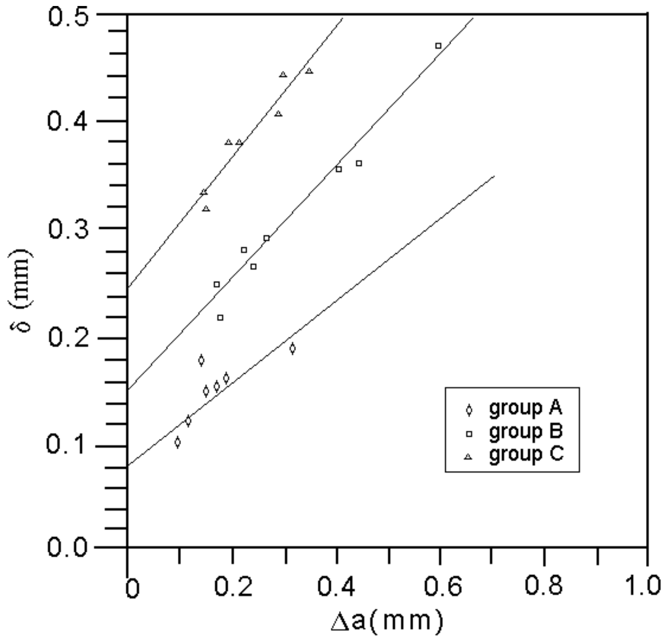

Figure 2: vs a of three groups of steel 17CrNi4 with a/w=0.1

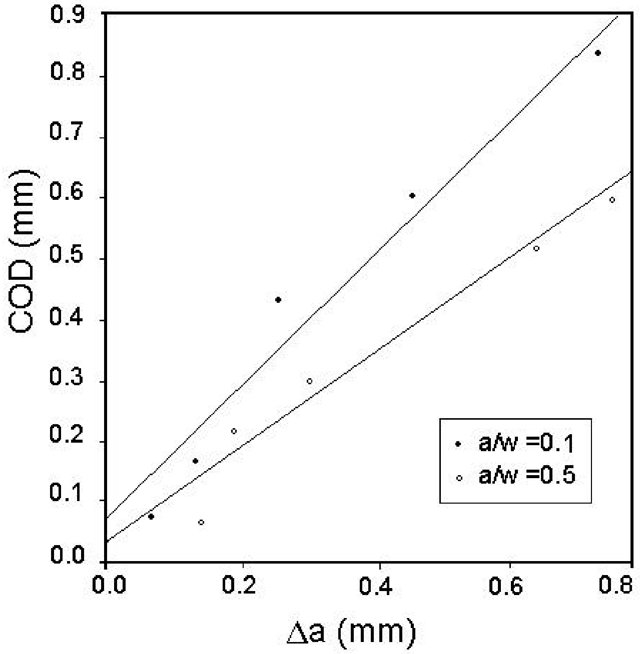

Figure 3: COD vs a of 40Cr steel

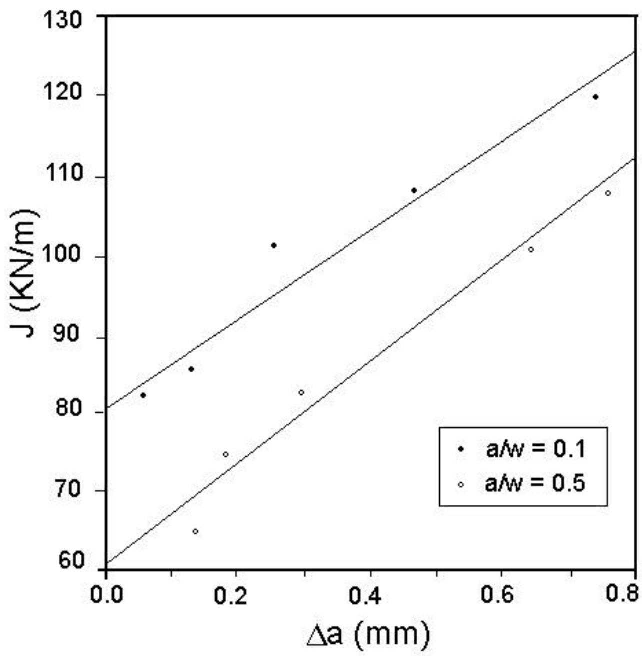

Figure 4: J vs a of 40Cr steel

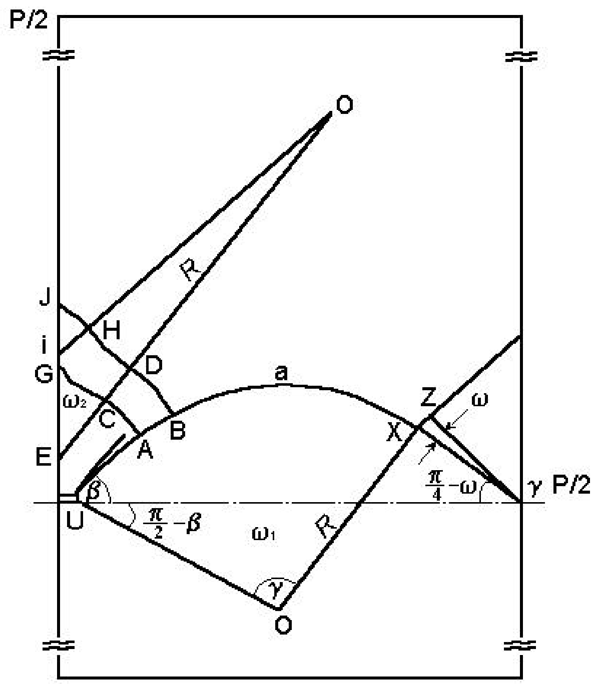

Figure 5: Slip-line field for a shallow crack in three-point bending

The theoretical developments [by J. W. Hancock et al] indicate that geometry dependent fracture toughness effects can be rationalized and united into one consistent scheme, through a two parameter characterization of elastic plastic crack tip fields and associated toughness [6,7].

Our experimental results are well in agreement with this Two Parameters Fracture Mechanics theory. Shallow cracked specimens (a/w<0.3) where T<0 exhibit increased toughness compared to deeply cracked ones, because their crack tip constraint is low. The state of constraint controls the triaxiality at the crack tip, and a low level constraint implies a low traixial stress field. The triaxiality controls the fracture process, and for specimens with a low triaxiality, the fracture toughness is known to be high.

We and some others, therefore, have pointed out that a typical fracture toughness obtained from a deeply cracked bend bar develops a high level of constraint, is known to be low. The standard fracture toughness test therefore provides a lower bound estimation, which ensure a safe but conservative value of the fracture toughness. It may lead to the imposition of prohibitive repair and inspection policies when applied to shallow cracks which are often found in structural components.
Therefore, the advantage of enhanced toughness for specimens with low levels of constraint should be taken into account for defect assessment, and a modified reasonable result should be taken for engineering applications.

CONCLUSIONS

1) Experimental results showed that shallow cracked specimens give markedly higher values of toughness than deeply notched ones.

2) Material data obtained from standard deeply cracked bend specimens which develop a high level of crack tip constraint, provides a lower bound estimate of toughness, will ensure an unduly conservative approach when applied to structural defects especially if initiation values of COD or J-integral are used.

3) Our experimental results are well in agreement with the Two Parameters Fracture Mechanics theory.

4) The advantage of enhanced toughness for specimens with low levels of constraint should be taken into account for defect assessment, and a modified reasonable result should be taken for engineering applications by using the TPFM method.

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