The Fracture Toughness of Spring Steel Containing Surface Cracks

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ABSTRACT

Fracture toughness tests have been carried out on spring steel using semi-elliptical cracked specimens with crack size and shape as variable. Effects of crack depth a, crack length c and the ratio a/c on fracture toughness have been studied and compared with the results of through-cracked ones. Results show that the toughness value is higher when crack depth is small. But the effect of crack shape on fracture toughness is negligible.

KEYWORDS

Fracture toughness K_{1c}; surface crack; 3-point bending.

INTRODUCTION

In standard plane strain fracture toughness (K_{1c}) tests, deep through-thickness cracks are often used (1). They, however, may not always be representative of the ones found in structural components, which are comparatively shallow and surface-breaking, often adopting semi-elliptical shapes. It is, therefore, of importance to study the fracture toughness values of semi-elliptical cracks and to know how this relates to the data for the through-thickness crack specimens.

Only a few experimental studies of the behaviour of surface cracks in testpieces have been reported in the literature (2). The present work attempts to compare the behaviour of three groups of specimens containing different shapes of semi-elliptical crack, and to study the effect of crack shape on fracture toughness.

EXPERIMENTAL PROCEDURE

The chemical composition and mechanical properties of spring steel 60Si2MnA used in the test are shown in table 1 .

Specimens were machined respectively in the configurations shown in fig.1 (a), (b), (c), such that each testpiece had a central 4 x 3 mm, 7 x 3 mm, 10 x 3 mm ridge respectively running along its length. This was provided with a central slot of width 0.25 mm and specimens were fatigue pre-cracked in three-point bending in a 100KN servo-controlled electro-hydraulic testing machine. The fatigue pre-cracks propagated through the ridge and then extended along the shoulders of the test-pieces. The applied loads were then progressively reduced to maintain a slow rate of crack extension until the required crack length was reached. The ridges were machined off after pre-fatiguing until their final appearance were as shown in fig.2 .

The shapes of the three groups of semi-elliptical crack were varied. The overall surface crack length varied from about 10 mm to 12mm, 7 mm to 9 mm, and 4 mm to 6.5 mm respectively. The crack depth varied from the minimum 0.58 mm to the maximum 2.83 mm .

Table 1. Composition and properties of spring steel 60Si2MnA

(a) Chemical analysis

C	Si	Mn	P	S	Cr	Ni
0.58	1.83	0.75	0.02	0.012	0.1	0.07

(b) Mechanical properties

Yield strength (MPa)	1001
Ultimate strength (MPa)	1068
Elongation (%)	7

Three-point-bend specimens testing was performed in a WJ-10 testing machine of 100KN capacity in accordance with BS5447:1977. P-V and P-Δ plots were simultaneously recorded on a X-Y-Y recorder. Two clip gauges were used. One was used to measure the crack mouth displacement V and the other was to measure the load-point displacement Δ.

Toughness values for semi-elliptical crack specimens were calculated using the relationship from Rook and Cartwright (4), i.e.

$$K_Q = 6QM(\pi a)^{1/2}/BW^2 \qquad (1)$$

where Q = crack shape factor, M = maximum bending moment, a = maximum crack depth, and W = specimen depth.

No compliance factor could be found in the literature for a semi-elliptical crack in 3-point bending, but 4-point bending data were available. In order to apply the analyses for pure bending to the present tests which were performed in 3-point bend, a correction has been applied. The stress σ_{max} has been taken as the maximum surface stress in 3-point bending and all the final toughness values have been reduced by 7 per cent to account for the difference between specimens compliance in 3- and 4-point loading [5].

As a further check, the very shallow cracks in bending were approximated to a uniform tension equal to the maximum elastic fiber stress in bending. Hence :—

$$K_Q = 1.12\sigma_{app}(\pi a)^{1/2} \quad (2)$$

where $\sigma_{app} = 6M/BW^2$, M is the applied bending moment. And the appropriate shape factor for a uniform tension was employed [4].

RESULTS AND DISCUSSION

The variation of fracture toughness K_Q with a/W ratios is shown in fig.3 , and the variation of K_Q with c/W ratios is shown in fig.4 , Fig.5 gives the relationship of K_Q with a/c . These results were also compared with the through-cracked specimens results obtained elsewhere, using the same material [2] , as shown in table 2 .

All the fracture appearance of broken specimens are completely square, with no proportion of slant at the edges. The validity of the results were judged on the same basis as for the standard testpieces. All the crack depths were less than the factor $2.5(K_Q/\sigma_y)^2$, although all other validity criteria were met, we take these results as "non-valid". (BS5447:1977)

The average K_Q results of the three groups of semi-elliptical crack specimens are 49.24 MPa$\sqrt{m}$, 48.93 MPa$\sqrt{m}$ and 48.33 MPa$\sqrt{m}$ respectively.These can be compared with the average K_Q value of shallow through-cracked specimens of 50.67 MPa$\sqrt{m}$. We may see reasonable agreement among these different types.
J.E.King and J.F.Knott once gave a different result for semi-elliptical cracks giving a toughness value which is almost 25

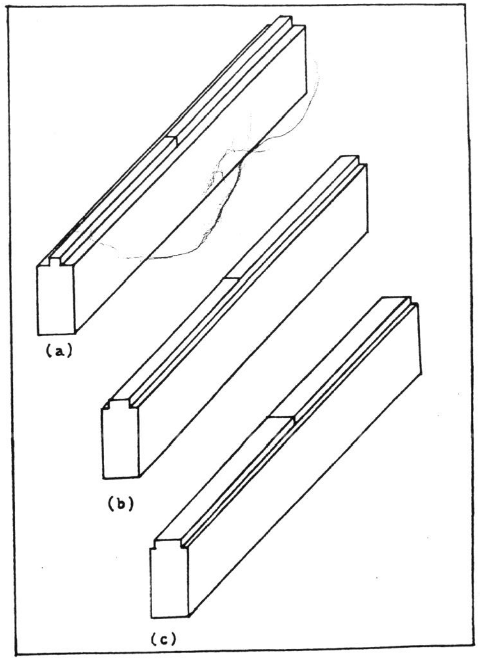

Fig. 1. Initial Design of three groups of surface-cracking specimens

per cent higher than the through-thickness one[5]. It may have been a material effect. For the material used in the present test, we may say that the effect of crack shape on fracture toughness is negligible.

However, compare the valid K_{1c} value of 40.44MPa$\sqrt{m}$ (from [2]) for deep through-cracked specimens with the K_Q values of all the shallow crack specimens (both through- and surface-cracked), the shallow crack specimens give a higher toughness value which is about 25 per cent higher than the deep crack ones. It means that the material is more resistant to crack growth when the crack is small.

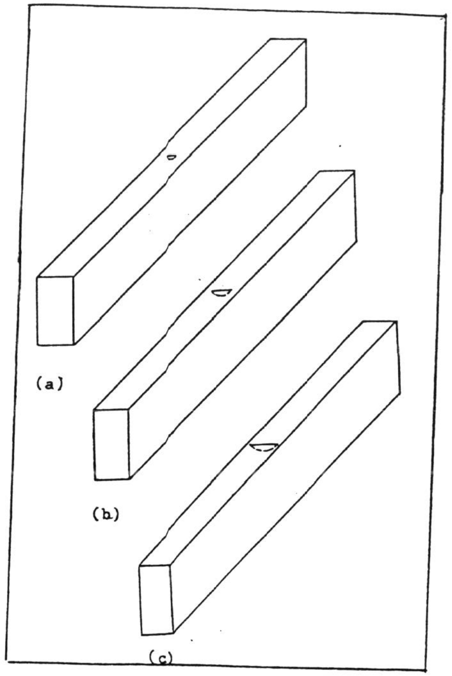

Fig.2. Final appearance of specimens after surface grinding

In engineering practice, crack depth is not allowed to be deeper than the critical crack size a_c, which is often very small. (For the material used in the present work, the appropriate defect sizes for $0.6\sigma_y$, $0.8\sigma_y$, and σ_y design stresses are 1.15 mm, 0.65 mm and 0.41 mm respectively.) Therefore, more work is needed to assess true values of toughness under shallow crack condition.

CONCLUSIONS

1. The effect of crack shape on fracture toughness is negligible.
2. The toughness value of shallow crack specimens is higher than deep crack ones.

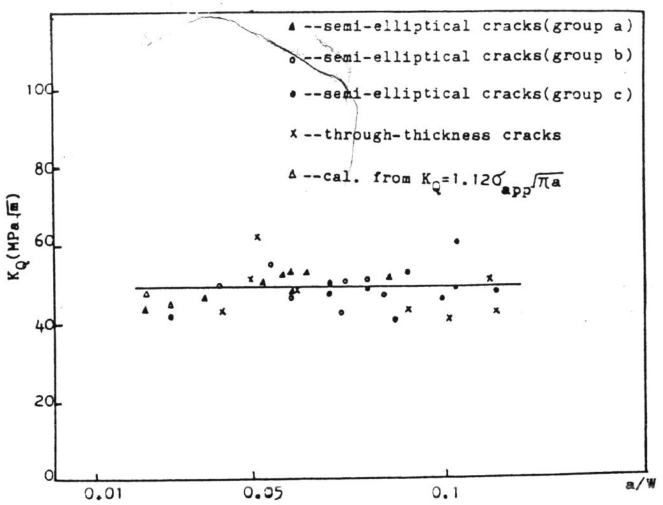

Fig.3. K_Q vs a/W

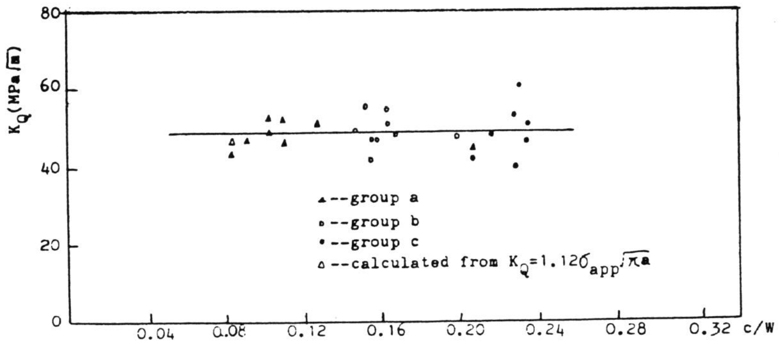

Fig.4. K_Q vs c/W

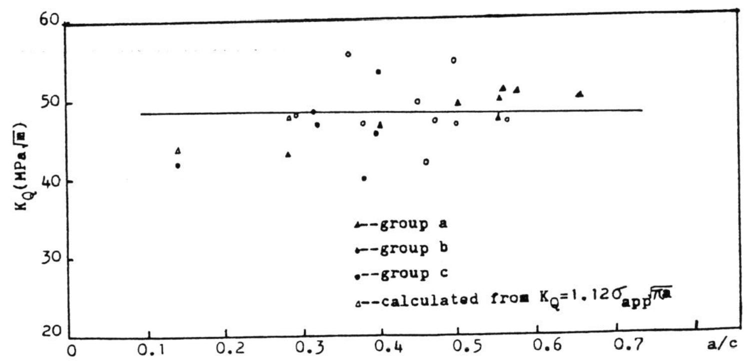

Fig.5. K_Q vs a/c

Table 2. Comparision of experimental results for through- and surface-cracked specimens

Through-cracked			Surface-cracked		
Spec. No.	a (mm)	K_Q (MPa $\sqrt{m}$)	Spec. No.	a (mm)	K_Q (MPa $\sqrt{m}$)
21	2.29	42.20	69	0.58	42.88
32	2.78	50.93	62	0.95	46.14
33	2.86	41.88	65	1.32	49.82
35	2.69	40.60	61	1.61	52.61
24	1.51	48.57	64	1.50	52.23
25	1.30	60.24	68	1.45	52.15
26	1.28	51.94	60	1.53	47.19
54	1.08	41.95	66	2.12	50.86
			72	1.83	41.37
			79	1.05	49.07
			70	2.00	48.11
			71	2.83	47.22
			77	1.98	46.66
			74	1.84	50.63
			75	2.01	55.01
			76	1.51	46.63
			73	1.37	55.67
			86	1.75	46.65
			80	2.18	39.98
			85	2.26	53.18
			83	2.58	61.47
			89	1.74	49.50
			84	2.31	45.89
			82	0.73	41.64

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