THE FRACTURE TOUGHNESS OF HIGH STRENGTH ENGINEERING ALLOYS CONTAINING SHORT CRACKS

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ABSTRACT

Fracture toughness tests have been carried out on a variety of high-strength engineering alloys using crack size and shape as variables. Results have shown that the LEFM approach to fracture is tenable for design stresses up to about two-thirds of the general yield stress. For short crack lengths, LEFM breaks down and elastic/plastic analysis is necessary to determine toughness. General-yielding and post-yield fracture mechanics methods indicate that local crack tip ductility and hence true material toughness increase at very short crack lengths.

KEYWORDS

Fracture toughness; High strength Marageing steel; High strength Aluminium Alloy; Short cracks; Semi-elliptical edge cracks; Post yield fracture.

INTRODUCTION

Standard linear elastic fracture mechanics (LEFM) is conventionally used without any correction for plastic-zone size to determine the plane-strain fracture toughness (K_{IC}) of high-strength engineering alloys. In turn, for a given design stress, LEFM can be used to calculate the critical crack size a_{crit}, below which a crack should not propagate under monotonic loading. For high design stresses, a_{crit} is small (< 1mm) and there is not much information in the literature concerning the behaviour of engineering alloys with cracks of such sizes. Standard fracture tests are carried out in deeply-cracked specimens ($^a/w = 0.5$) and the calculated toughness values are assumed to remain constant down to critical crack size. In very high-strength engineering alloys, this size can be so small as to be beyond the limit of most NDT techniques and so it is important to assess the behaviour of short cracks representative of service conditions. A series of plane-strain fracture toughness tests has therefore been carried out on a variety of alloys using the crack size as the main variable. The alloys tested were:- two high strength 18%Ni Marageing steels, designated G150 and G125 (G150: 0.2% proof stress = 2.4GPa. G125: 0.2% proof stress = 1.9GPa), a 7010 series Aluminium alloy (0.2% proof stress = 0.6GPa) and a 1.5Cr 0.5Ni 0.25C high strength low alloy steel (tested at 77K where the 0.2% proof stress = 1.7GPa). The deep-crack K_{IC} values of these alloys varied from 34 to 121MPam$^{\frac{1}{2}}$. The tests were carried out over a range of crack sizes down to and below values of a_{crit} corresponding to typical design criteria.

TABLE 1 Nominal alloy compositions (wt%)

Material	Ni	Co	Mo	Ti	Al	Fe
G150 Marageing steel	17.5	12.5	3.75	1.8	0.15	bal.
G125 Marageing steel	18	9	5	0.6	0.1	bal.

Material	Zn	Mg	Cu	Zr	Fe	Si	Al
7010 Al Alloy	6.2	2.5	1.7	0.14	0.11	0.07	bal.

High strength low alloy steel: 0.5Ni. 1.5Cr. 0.25C.

EXPERIMENTAL

Single-edge-notched (S.E.N.) bend specimens were prepared with one of two crack shapes - either standard "through-thickness" or "thumbnail" (Wiltshire and Knott, 1980). All the specimens were fractured in 3- or 4-point bend in a Mand servo-controlled electro-hydraulic testing machine in accordance with BS 5447 (Ref.2) apart from testpiece geometry. Toughness values for "through-thickness" specimens were calculated using a standard linear elastic relationship for S.E.N. bend specimens

i.e. $K_Q = PY/BW^{\frac{1}{2}}$ (1) where P = load to failure, Y = specimen compliance, B = specimen width and W = specimen depth.

The measured crack sizes only were used for the initial toughness calculations, i.e no allowance was made for the increasing ratio of crack size/plastic zone size as the crack size was reduced. The compliance values were taken from Gross and Srawley (1965) and confirmed by extrapolation of the data of Walker and May (1967). As a further check, the very short cracks in bending were approximated to the situation of an edge-crack submitted to a uniform tension equal to the maximum elastic fibre stress in bending, hence:-

$$K_Q = 1.12\,\sigma_{app}\,(\pi a)^{\frac{1}{2}} \qquad (2)$$

The thumbnail-crack specimens were tested in 3- or 4-point bend and the toughness values were calculated using the relationship from Rooke and Cartwright (1976) i.e. $K_Q = 6QM\,(\pi c)^{\frac{1}{2}}/BW^2$ (3) where Q = crack shape factor, M = maximum bending moment, c = maximum crack depth and W = specimen depth. No compliance factor could be found in the literature for a thumbnail crack in 3-point bend, but 4-point bend data were available and these were used in a modified form. In addition, the results were confirmed by use of the stress analyses of Pickard (1980) and Randall (1967). As a further check on toughness, eqn.(2) was used with an appropriate shape factor for small thumbnail cracks. This gave results which lay within 5% of the alternative calculations.

RESULTS AND DISCUSSION

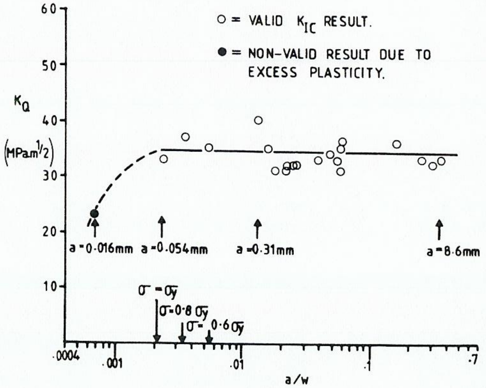

Fig. 1. G150 (L-ST) Marageing steel. Plot of apparent toughness against log $^a/_W$.

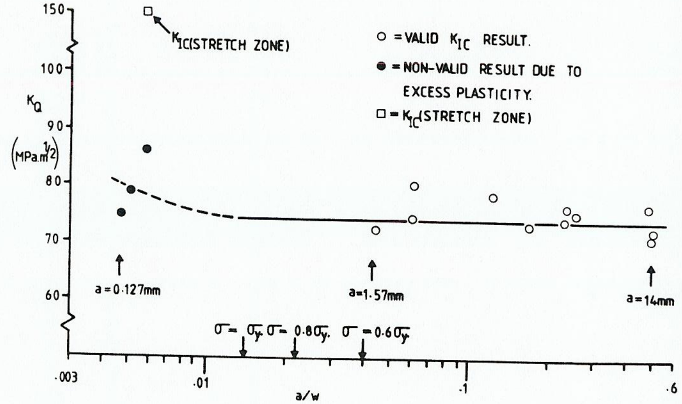

Fig. 2. G125 (L-ST) Marageing steel. Plot of apparent toughness against log $^a/_W$.

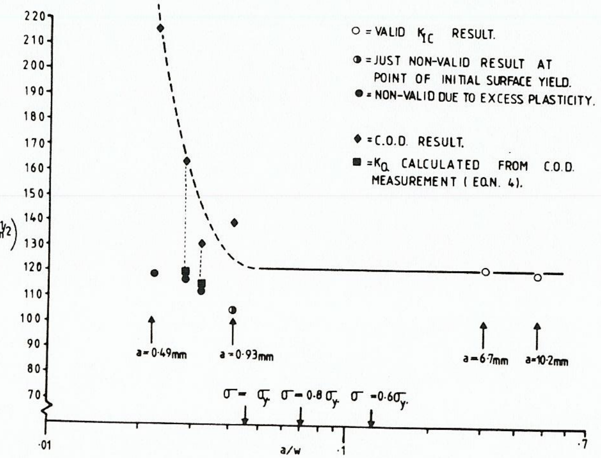

Fig. 3. G125 (L-T) Marageing steel. Plot of apparent toughness against log $^a/_W$.

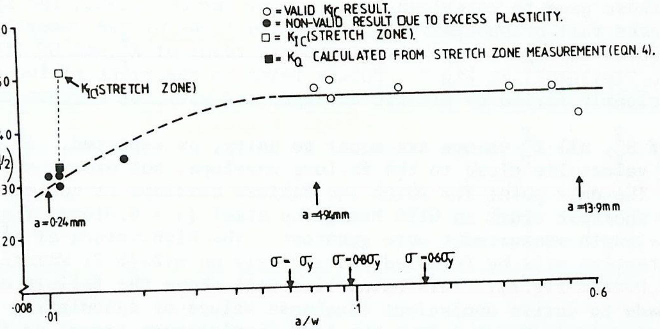

Fig. 4. 7010 Aluminium Alloy. Plot of apparent toughness against log $^a/w$.

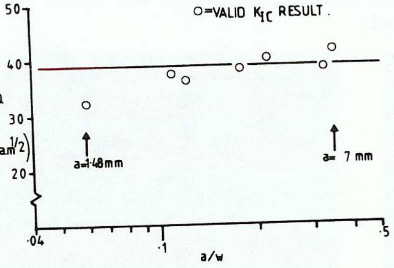

Fig. 5. 0.5Ni, 1.5Cr, 0.25C steel. Plot of apparent toughness against log $^a/w$ (tested at 77K).

Linear elastic results

Figures 1-5 show the variation of toughness (K_Q) with $^a/w$ for the "through-thickness" test series. In all cases, the K_Q values are observed to remain relatively constant down to quite short crack lengths. The load/clip gauge displacement traces were linear for all crack sizes, down to the limit, at which the applied (fracture) stress was coincident with initial surface yield. This is approx. two-thirds of general yield for bend specimens containing short cracks. It seems reasonable therefore to designate all K_Q values associated with linear traces as valid plane strain results. At crack sizes smaller than this, specimen plasticity is evident in the load traces and an elastic/plastic analysis is necessary to determine toughness.

Using LEFM criteria it is possible to calculate, for any given design stress, a critical crack size a_{crit}, below which the crack should not propagate under monotonic load. Table 2 gives the critical crack sizes for the alloys tested with design stresses of 0.4, 0.53 and 0.66 of the general yield stress ($0.6\sigma_y$, $0.8\sigma_y$ and σ_y).

Figures 1-5 show that "valid" plane strain fracture toughness results generally remain constant down to a_{crit} (at $\sigma = \sigma_y = 2/3\sigma_{GY}$). For example in G150 Marageing steel (fig.1) the deep crack K_{IC} ($^a/w = 0.5$, $a = 11$mm) is 34MPam$^{\frac{1}{2}}$ and K_Q for a crack length of 0.054mm (a_{crit} for $\sigma = \sigma_y = 2/3\sigma_{GY}$) is 32.8MPam$^{\frac{1}{2}}$. The lower strength Marageing steel (fig.2 - G125 (L-ST)) shows similar agreement with LEFM criteria:- the deep crack K_{IC} = 76MPam$^{\frac{1}{2}}$ ($^a/w = 0.5$, $a = 14$mm) and, at a crack size of 1.57mm, the K_Q value is 73MPam$^{\frac{1}{2}}$ It may be noted here that to maintain plane-strain conditions in short crack specimens it was necessary to increase the thickness (B) to 7.6 $(K_{IC}/\sigma_y)^2$. Fracture toughness tests in G125 L-T orientation (fig.3) show a similar trend with the deep crack K_{IC} value of 121MPam$^{\frac{1}{2}}$ remaining constant down to a crack size of 0.93mm, which was just coincident with top surface yield. The 7010 series aluminium alloy tests show a useful comparison with Marageing steel because both materials exhibit a ductile void coalescence mode of failure. In addition the deep crack K_{IC} value of 7010, at 46MPam$^{\frac{1}{2}}$, is of the same order as that for high-strength Marageing steel, but the yield strength is much reduced (σ_y = 590MPa). Consequently, it was easier to produce a range of crack sizes much smaller than a_{crit} at $\sigma = \sigma_y$ (1.54mm). The results (fig.4) show as before, that the valid K_{IC} results remain constant at 46MPam$^{\frac{1}{2}}$ virtually down to the conditions for initial top surface yield (experimentally, down to 1.94mm). The 0.5Ni, 1.5Cr, 0.25C steel specimens (fig.5) were tested at 77K where the fracture mode was transgranular cleavage. Again the K_{IC} results remain reasonably constant at 39MPam$^{\frac{1}{2}}$ down to a crack size of 1.48mm.

TABLE 2. Critical crack sizes for various design stresses

Material	K_{IC} (MPa.m$^{\frac{1}{2}}$)	a_{crit} (edge crack: $K_{IC}=1.12\sigma_{app}(\pi a)^{\frac{1}{2}}$ (mm))		
		$0.4\sigma_{GY}$ ($0.6\sigma_y$)	$0.53\sigma_{GY}$ ($0.8\sigma_y$)	$0.66\sigma_{GY}$ (σ_y)
G150(L-ST)	34	0.14	0.08	0.05
G125(L-ST)	76	1.10	0.62	0.4
G125(L-T)	121	2.86	1.61	1.03
7010 Al Alloy	46	4.26	2.40	1.54
0.5Ni, 1.5Cr steel (77K)	39	0.37	0.21	0.13

The results from the fracture toughness tests on G125 with thumbnail shaped cracks are shown in fig.6. The same criteria have been used to assess validity as in the "through-thickness" case. Therefore K_Q results are considered to be valid K_{IC}

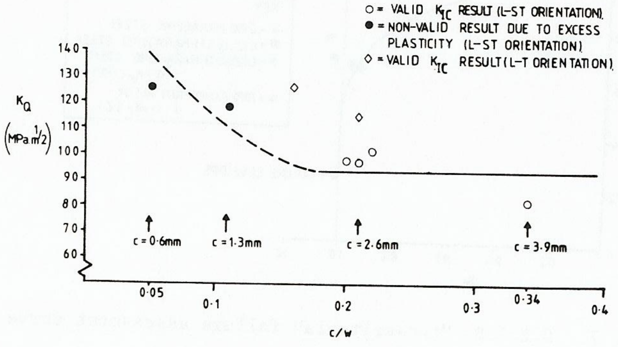

Fig. 6. G125 Marageing steel. Plot of apparent toughness against $^c/w$ (thumbnail cracks).

values provided that the specimen has not yielded on the top surface. The average valid K_{IC} result for thumbnail specimens in the L-ST orientation is 95MPam^{½} - this can be compared with a value of 76MPam^{½} for "through-thickness" specimens, i.e. a difference of 26%. Three independent stress analyses were used for the thumbnail calculations and so it is unclear at present why this difference in toughness value exists. Additionally, two results were obtained for thumbnail specimens in the L-T orientation. However these gave results which were very close to the "through-thickness" case. The specimens with very small thumbnail cracks yielded before fracture.

Elastic/Plastic analysis of short cracks

When the fracture stress is a substantial fraction of the general yield stress, the load-displacement curve displays marked non-linearity and linear-elastic stress analyses are no longer applicable. In deeply-cracked specimens, non-linearity is associated with crack-tip plasticity, but for the short cracks in the present experiments (fracture stresses greater than $^2/3\ \sigma_{GY}$), surface yielding has occurred, and non-linearity may be attributed to specimen plasticity as much as to the crack-tip plasticity. Under "small-scale yielding" conditions in deeply-cracked pieces, the effect of plasticity on the effective stress-intensity is judged to be equivalent to the replacement of the crack length, a, in standard formulae, by an "equivalent crack length" $(a + r_y)$ where r_y is the plastic-zone "radius", given by $r_y = (1/2\pi)(K/\sigma_y)^2$. At higher fractions of general yield, a plane-stress model gives the extent of plasticity, dy ($\simeq 2r_y$) as $dy = a\{\sec(\pi\sigma_{app}/2\sigma_y)-1\}$, and, if K_{IC} is defined as $(E\sigma_y\ \delta_c)^{½}$, the ratio, K_r^f, of "apparent" toughness, $\sigma_F(\pi a)^{½}$, to K_{IC} is given by:

$$K_r^f = S_r^f\ \{(^8/\pi^2)\ \ln\sec(\pi S_r^f/2)\}^{-½} \qquad (4)$$

where $S_r^f = \sigma_F/\sigma_{GY}$. This expression is the basis of the failure envelope in the CEGB "R6" design "route", which recognises that a structure can fail either by fast fracture or by plastic collapse, (Milne, Loosemore and Harrison, 1978), but modifies the stress analysis to allow for substantial (crack-tip) plasticity before fracture. The modification reduces to the "equivalent elastic crack" form for low σ_F/σ_{GY}. The results in the present paper provide a means of establishing an experimental failure envelope for plane-strain fracture, in a range of materials different from those used to establish the C.E.G.B. curve, because the specimens with shorter cracks fail at successively higher fractions of the general yield stress. The results in Figs. 1-4 are replotted in terms of K_r^f and S_r^f (the index "f" referring to "failure") in Fig.7. Points lying to the right of the vertical line Sr=1 have clearly failed by plastic collapse and will not concern us further.

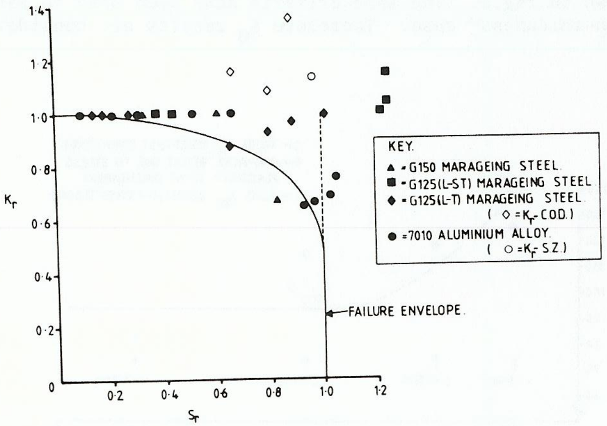

Fig. 7. C.E.G.B. "two-criteria" failure assessment curve.

At low values of S_r^f, all K_r^f values are equal to unity, as expected. At higher S_r^f ratios, some K_r^f values lie close to the failure envelope, but others are significantly higher. The only point for which the failure envelope is non-conservative is that for the shortest crack in G150 Marageing steel (a = 0.016mm, fig.1), where errors in crack-length measurement were greatest. The high values of K_r^f are of interest and attention will be focussed particularly on G125(L-T) Marageing steel (S_r^f = 0.89, a = 0.63mm fig.3). This point lies well above the failure envelope. Attempts were made to derive equivalent toughness values by calculating the crack-tip opening displacement (C.O.D.) from the load displacement traces or from stretch zone widths. These results are shown in Figs. 2,3 and 4 and appear to indicate a marked increase in material toughness (crack tip ductility) as the crack length decreases. The G125 Marageing steel stretch zone width is shown in Fig.8. This could be attributed to relaxation of the constraint around the crack tip as surface-yielding becomes more pronounced.

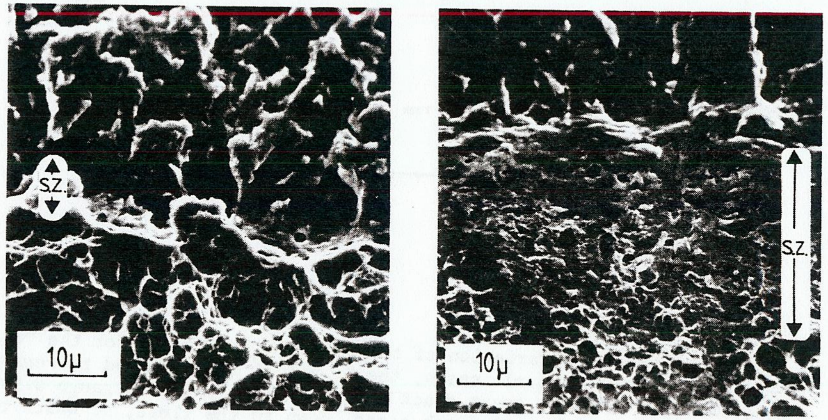

Fig. 8. Comparison of deep and short crack tip stretch zones in G125 Marageing steel.

The final apparent toughness, K_Q, then appears to be a combination of two factors. In terms of Fig.7, K_r^f would be expected to decrease at high S_r^f because of the effect of plasticity on stress analysis, but to increase if the material's toughness increases. The net effect on K_Q may be such that it appears to be little different from K_{IC} ($K_r^f \simeq 1$) i.e. in G125(L-T) Marageing steel (fig.3) the deep crack K_{IC} value = 121MPam^{½}, C.O.D. measurements predict a toughness of 163MPam^{½} whereas the K_Q value is 118MPam^{½}.

CONCLUSIONS

Fracture toughness tests have been carried out on a variety of high strength alloys using crack size as the main variable. The results have shown that the LEFM approach to fracture is tenable (in both cleavage and fibrous fracture mode) for design stresses as high as two-thirds of the general yield stress. Elastic/plastic analyses have shown that at crack sizes smaller than a_{crit} ($\sigma = \sigma_y = {}^2/_3\, \sigma_{GY}$) crack tip ductility and hence "true" toughness is increased. In the orientation for which the majority of results have been obtained, thumbnail crack specimens appear to exhibit a higher K_{IC} value than for similar specimens with "through-thickness" cracks, but this may be due to the lack of accurate stress analysis for thumbnail cracks in bend specimens. The "through-thickness" fracture results have been discussed in terms of the CEGB "two-criteria" failure assessment curve. At short crack sizes, some K_Q values appear to be a compromise between effects of plasticity on the elastic stress analysis and an increase in local crack tip ductility.

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