The Effect of Pre-cracking Variables R and K_{FMAX} on Fracture Toughness

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ABSTRACT

A study was made of the effect of the pre-cracking variables, the maximum value of the fatigue stress intensity factor K_{fmax} and the stress ratio, R, on the resulting value of fracture toughness K_q. The tests were conducted on a 4130 alloy steel heat treated to 180 ksi yield strength. A nominal value of K_q based on fracture tests following ASTM standards of 70 ksi(in)$^{1/2}$ was used in the analysis.

The results showed variations in the resulting fracture stress intensity that could not be considered random in nature. At a K_{fmax} of about 40 ksi(in)$^{1/2}$ corresponding to about 0.57 K_{Ic} (K_q) the apparent fracture toughness values show a distinct minimum. This occurs for all values of R examined, 0.1, 0.3, 0.5, and 0.7. This indicates that the requirement of ASTM E399 for $K_{fmax} = 0.6\ K_{Ic}$ is sufficiently strict so as to produce a lower bound estimate of fracture toughness. Test(s) conducted with constant K_{fmax} at varying fatigue ratios, R, show variations that indicate there exists a maximum value of apparent fracture toughness. The location of the maximum depends upon the value of R chosen and the magnitude of K_{fmax}. A simple model for this effect has been proposed that considers the opposing effects of crack closure during the fatigue cycling and the crack tip "sharpening." It is apparent that the value of apparent fracture toughness obtained using the appropriate testing standards is not necessarily the lowest value of fracture toughness that the material can exhibit.

KEYWORDS

Fracture toughness; fatigue precracking; fatigue stress ratio.

INTRODUCTION

The ASTM Committee E-24 standard E399 and the comparable British Standard BS5447 both place detailed restrictions on the specimen size requirements and the fatigue pre-cracking requirements necessary to obtain a valid lower bound estimate of plane strain fracture toughness K_{Ic} or its equivalent. The rationale for the size and thickness requirements is easily understood; in order to produce a valid condition of plane strain, the thickness and specimen size must be approximately 50 times larger than the plane strain plastic zone size at the crack tip (Brown and

Srawley, 1970a; 1970b).

The fatigue pre-cracking requirements are more complex, and the rationale for their restrictions is less direct. The "sharpness" of the fatigue crack depends upon the maximum value of the stress intensity K_{fmax} that is used to introduce and grow the crack. The fatigue stress ratio, R, determines the range of stress intensity applied during the fatigue pre-cracking for a given K_{fmax}, and is kept as low as possible to grow the crack to the required length in the shortest possible number of cycles. The straightness of the crack front has been reported to increase with increasing R, so that the crack front straightness requirement would suggest a higher R value (May, 1970).

The purpose of this study was to evaluate the effect of several fatigue pre-cracking variables on the resulting values of fracture toughness of a medium strength alloy steel, and see if some of the restrictions could be relaxed. In particular, the fracture testing of welded sections could be improved if the R value and K_{fmax} could be modified so as to produce straighter crack fronts during fatiguing (Towers and Dawes, 1985).

BACKGROUND

The Effect of Fatigue Pre-Crack Stress Intensity, K_{fmax}

The effect of increasing K_{fmax} during the final pre-cracking phase usually results in an increase in the resulting value of fracture toughness. Brown and Srawley (1970a) showed that K_q values obtained on 300 maraging steel (yield 283 ksi) increased when the K_{fmax} was set beyond 0.6 K_q. This increase was attributed to crack tip blunting since similar increases in K_q were observed in sharp machined notches compared to fatigued specimens. The magnitude of the effect of the value of K_{fmax} was assumed to depend on the alloy and the yield strength. Brown and Srawley (1970b) believed that additional testing on other materials would be necessary to better define the effect. Until such a time, the limit on K_{fmax} was kept at $0.6K_{IC}$.

Lower values of K_{fmax} are not usually desired since this would result in longer times to produce the desired crack length and this increases the time to produce fracture testing results. The 0.6 K_{IC} limit assumes that these tests result in the lower bound estimates of K_{IC}, i.e., conservative estimations. One could not be sure without testing that lower K_{fmax} values would not produce lower values of K_q, and there might be fatigue stress levels in service that would fail at lower applied stress intensity values that the experimentally determined K_{IC}.

May (1970) showed that maximum fatigue stress intensities could be increased to 80 to 90% of the resulting fracture toughness values with negligible increases in the resulting K_q. His suggestion of a maximum value of 0.67 K_{IC} for K_{fmax} is incorporated in the British BS5447 standard.

Kaufman and Schilling (1974) evaluated the effect of K_{fmax} on the fracture toughness of aluminum alloys. Using compact tension specimens it was observed that K_q was independent of K_{fmax} up to fatigue levels of 0.75 K_{Ic}. The fracture toughness increased for fatigue levels above this value. It was felt that this effect might only apply to aluminum alloys. Dowling (1977) evaluated the effect on a medium strength pressure vessel steel and an aluminum alloy. Clark (1979) showed that K_q increased as much as 40% for fatigue levels over 0.7 K_{Ic}. However, as the K_q increased, the thickness requirement was invalidated so the results were ambiguous.

Other experiments and reviews (Towers and Dawes, 1985; Towers, 1982) indicated that an increase in K_q could occur with increases in the maximum value of fatigue stresses, but there were no clear indications on the maximum value that should be allowed, or to evaluate the effect of lower values of K_{fmax}. It was suggested by Towers (1982) that the limits on K_{fmax} in BS5762 appeared to be sufficiently restrictive.

ASTM E399 requirements allow a maximum fatigue stress of 0.8 K_q for the initial fatigue pre-cracking, but the terminal portion of the fatigue pre-cracking should not exceed $0.6K_q$ if the test is to produce a valid value of K_{IC}. Actual fatigue testing practice often limits the maximum fatigue stress intensity levels to less than 0.8 K_q. Retardation of susgequent crack growth may occur during the change in stress from the initial pre-cracking phase to the terminal cracking phase if the fatigue stress level changes are too abrupt. Similar restrictions apply for CTOD of J fracture testing.

The Effect of R

The present restriction on $R < 0.1$ maximizes the load range and the rate of growth of the fatigue crack. Values of R other than 0.1 are discouraged by the test standards. The reason for the restriction is undocumented.

Towers (1982) showed that considerable variations could be expected in CTOD and K_q for R = 0.1 and 0.5, with K_{fmax} kept constant. His results are summarized in Figure 1. The data for R = 0.5 shows more scatter at low values of K_{fmax} than at higher values of K_{fmax}. For R = 0.1 the value of CTOD increases with increasing value of K_{fmax}.

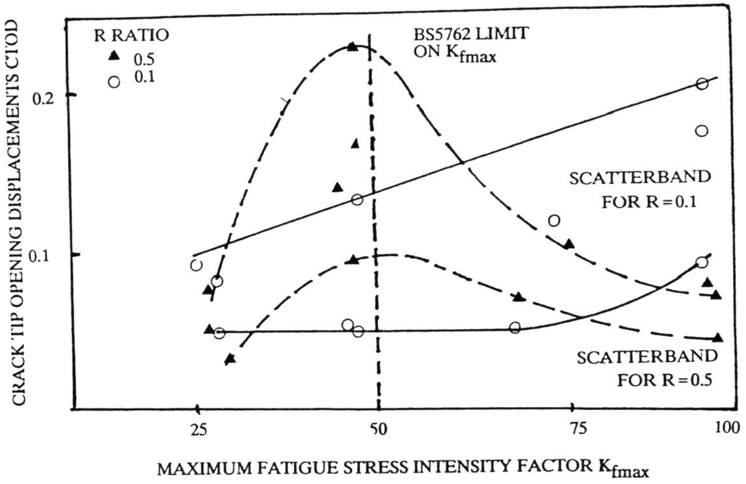

Figure 1 EFFECT OF R RATIO ON FRACTURE TOUGHNESS, CTOD

EXPERIMENTAL PROGRAM

The material used in this investigation was 4130 steel heat treated to 180 ksi yield strength (220 ksi ultimate). Single edge notch bend specimens with a span to width ratio of 4:1 were used. All dimensions, and pre-cracking were carried out following ASTM and British Standards with the exception that both R and K_{fmax} were varied. All specimens were pre-cracked to 97.5% of the final length and final pre-cracking was carried out using a test matrix with R ratios of 0.1, 0.3, 0.5, and 0.7 and values of K_{fmax} of 0.18, 0.34, 0.51 and 0.68 K_q. A nominal value for the fracture toughness of 70 ksi(in)$^{1/2}$ was used for the test program. A total of 16 different pre-cracking conditions were examined with at least three replications of K_q for each combination of R and K_{fmax}.

After fatigue pre-cracking was completed, the specimen was ramp loaded to fracture at room temperature at an approximate rate of 43 ksi(in)$^{1/2}$/min until fracture. Crack front straightness and all other conditions for valid K_{IC} tests were met. K_q was calculated using the appropriate formula.

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of K_{fmax}

Figure 2 shows the results of the experimental values of apparent fracture toughness K_q as a function of K_{fmax} for constant values of fatigue ratio R. The maximum fatigue stress intensity was varied from about 0.18 K_q to 0.68 K_q, corresponding to 10 ksi(in)$^{1/2}$ to 60 ksi(in)$^{1/2}$. Considerable variations in estimates of fracture toughness are observed to occur with changes in test conditions. These variations cannot be considered to be due to scatter in the test results. K_{fmax} values above 0.6 K_q were found to overestimate K_{IC} values of fracture toughness as reported in other investigations. It appears that the restriction of the maximum fatigue stress intensity to a value less than 0.6 K_q in the appropriate standard is sufficiently stringent.

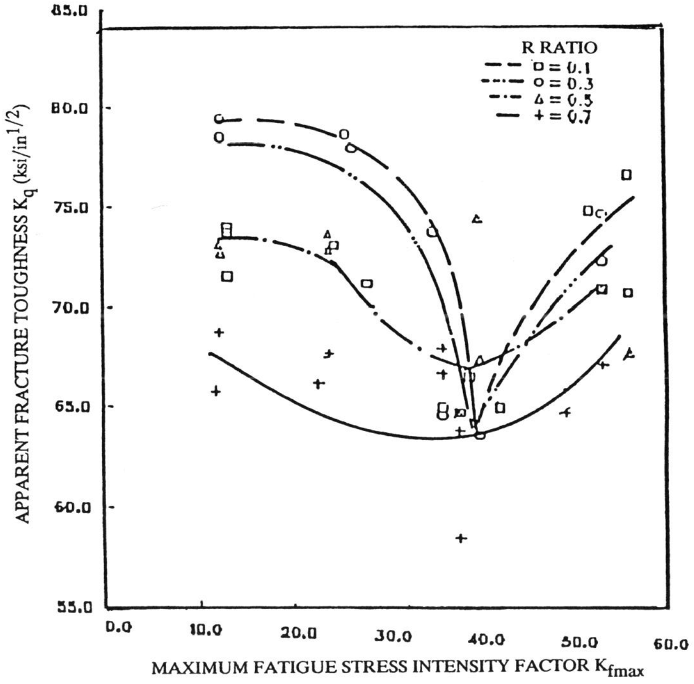

Figure 2 EFFECT OF MAXIMUM FATIGUE STRESS INTENSITY FACTOR K_{fmax} ON APPARENT FRACTURE TOUGHNESS K_q

All of the results showed a significant drop in the apparent fracture toughness at about 40 ksi(in)$^{1/2}$, corresponding to a value of about 0.57 K_q. The observed apparent fracture toughness increases for maximum fatigue stresses above and below this value. It is perhaps fortuitous that this minimum is found close to the ASTM recommended value of K_{fmax} equal to 0.6 K_{IC}. Results obtained from a different material might show the minimum at some other value of K_{fmax}. It appears that for this material the requirements are sufficiently stringent, so that a lower bound value of fracture toughness is the result, which is essentially independent of the value of fatigue stress intensity ratio R.

The effect of R at a constant maximum fatigue stress intensity was to significantly increase the difference between the minimum values of apparent fracture toughness found at this value of K_{fmax} and the values found at other K_{fmax} levels. The range of apparent fracture toughness was the greatest at the low R ratios and decreased as R increased.

Figure 3 shows the experimental values of apparent fracture toughness K_q as a function of R for the values of K_{fmax} evaluated. R ratios greater than 0.1 can be used to determine fracture toughness values that appear to be within those obtained using the recommended R values from the standards. The value of fracture toughness using R values greater than 0.1 resulted in lower bound values that did not differ statistically from those obtained using the recommended procedures.

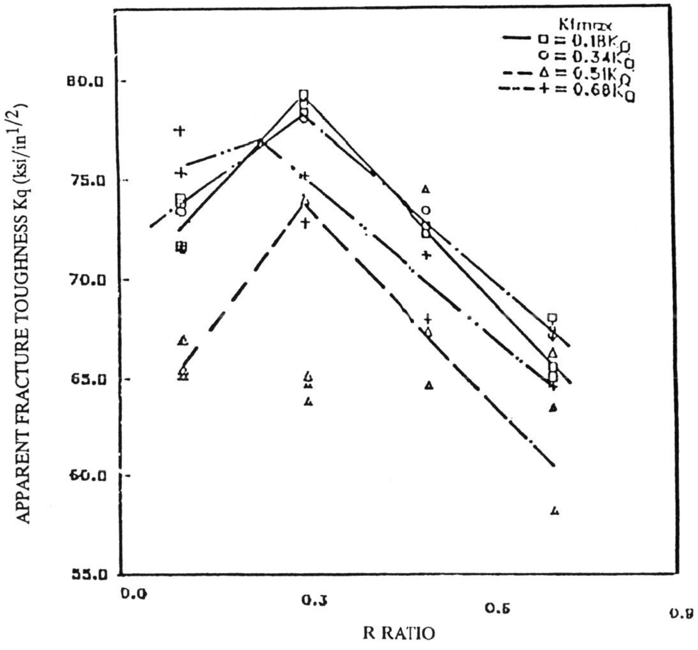

Figure 3 EFFECT OF R RATIO ON APPARENT FRACTURE TOUGHNESS K_Q

The tendency for the fracture toughness to be higher at higher R values for a given K_{fmax} is consistent with Elber's model of crack closure. Keeping K_{fmax} constant with increasing R increases the value of the stress intensity required to open the crack tip as seen in Figure 4. When the specimen is unloaded and tested monotonically to fracture, the measured value of K_q includes the stress intensity required to open the crack and then to cause the crack propagation. Thus one would expect an increase in apparent fracture toughness with increasing R if the maximum fatigue stress is kept constant. This would be correct as long as the minimum value of the fatigue stress intensity were below the stress intensity required to open the crack K_{c1}. However, if the increase in R results in "sharpening" the crack tip due to strain hardening, one would expect a decrease in the measure of fracture toughness with increase R with K_{fmax} held constant.

These two conflicting processes are illustrated schematically in Figure 5. The position of maximum apparent fracture toughness would be the point where the R value was equal to K_{c1}/K_{fmax}. Beyond this value of R the range of applied stress intensity would be less than the range of maximum stress intensity to closure stress intensity, and the crack could sharpen. Figure 6, as an example, shows that this is true for $K_{fmax} = 0.18\ K_q$. Using other data for this material obtained as part of this investigation, the value of K_{c1} was found. The location of the maximum according to this simple model was about R = 0.3.

No effect of R or K_{fmax} was observed on the shape of the crack front. For a material for which R does influence the crack front shape, higher R ratios could be used to straighten the crack front to comply with the secondary restrictions in the standards with no statistically significant change in the measure fracture toughness value, provided the R was greater than 0.3 and beyond the maximum on the curve.

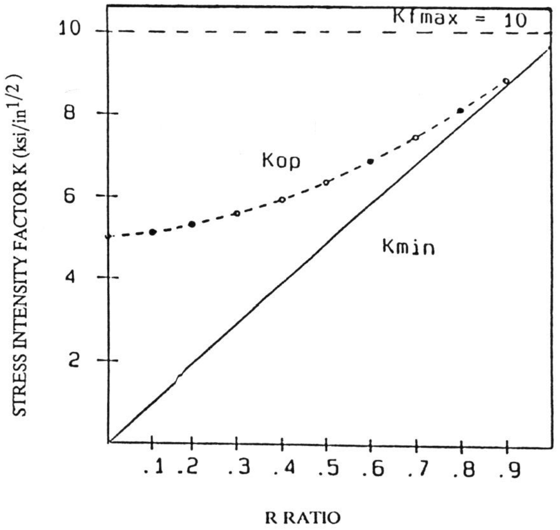

Figure 4 STRESS INTENSITY TO OPEN CRACK (K_{op}) AS A FUNCTION OF R FOR CONSTANT K_{fmax}

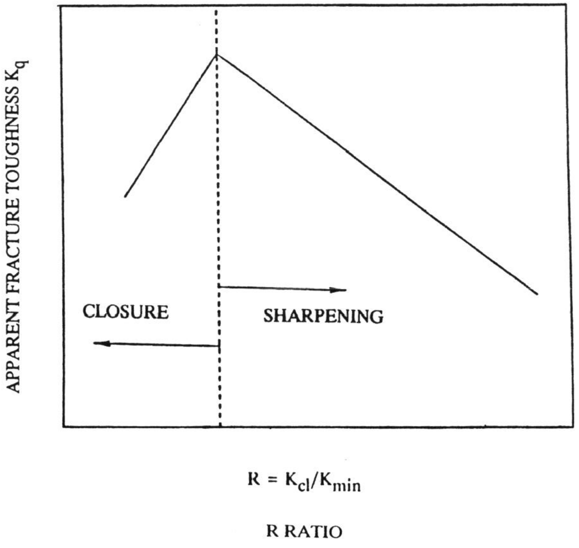

Figure 5 SCHEMATIC SHOWING EFFECTS ON APPARENT FRACTURE TOUGHNESS OF CLOSURE AND CRACK SHARPENING AS A FUNCTION OF R RATIO

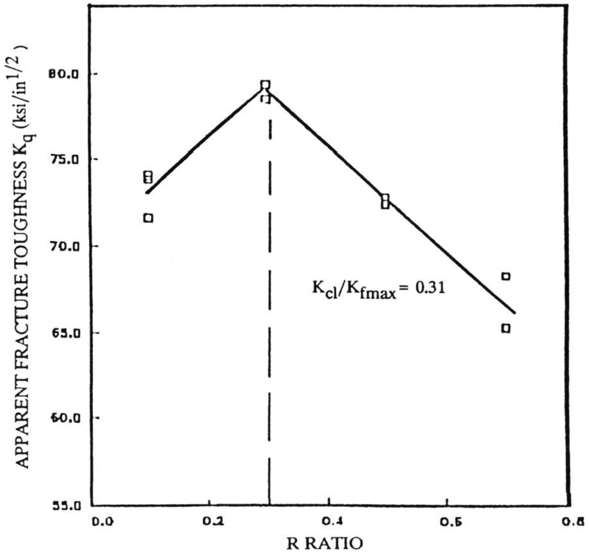

Figure 6 LOCATION OF MAXIMUM VALUE OF APPARENT FRACTURE TOUGHNESS BY MODEL OF FIGURE 5. $R=K_{cl}/K_{fmax}$. $K_{fmax}=0.18\ K_q$

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