Fracture 1977, Volume 3, ICF4, Waterloo, Canada, June 19 - 24, 1977

INVESTIGATION OF THE FRACTURE TOUGHNESS OF CONSTRUCTIONAL STEELS IN CYCLIC LOADING

V. T. Troshchenko, V. V. Pokrovsky and A. V. Prokopenko*

INTRODUCTION

At present, by using linear fracture mechanics methods, it is possible, with static load application, to determine quite reliably the ultimate carrying capacity of structural elements with cracks from results of tests on laboratory specimens, if the material is brittle and in plane strain. Conditions of reproducibility of test results are mentioned in some standards [1]. Nevertheless, the majority of brittle failures occurs as a result of a crack reaching critical size under a cyclic load. The conditions for such a fracture have not been studied sufficiently. This paper considers this problem.

TECHNIQUE AND TEST RESULTS

Constructional ferrite-pearlite steels were studied; steel 1, 0.15% C, σ_f = 501 MPa; steel 2, 0.1% C, σ_f = 617 MPa.

Round cantilever specimens with gauge diameter of 0.015 m were tested in rotating bending at 50 Hz. The installation is described in [2]. Tests were conducted at 77 K to ensure brittle fracture under plane strain conditions. Since for a circular specimen with a one-sided crack there is no exact analytical solution for the stress intensity factor, K_I, the technique of experimental determination of K_I and K_{Ic} based on measuring elastic compliance of the crack specimen [2] was used. The value of elastic energy release was calculated by the formula:

$$G_I = \frac{P^2}{2} \cdot \frac{d(f/P)}{dF} \qquad (1)$$

where P = load; f = specimen deflection at the point of load application; F = crack area.

From this value of G_I, the value of K_I for plane strain was obtained from:

$$K_I^2 = \frac{E}{1-\nu^2} G_I \; . \qquad (2)$$

From (1), for a cylindrical specimen:

$$K_I = \sigma D^{1/2} Y \; , \qquad (3)$$

* Institute for Problems of Strength, Academy of Sciences of the Ukrainian S. S. R., 252014 Kiev 14, U. S. S. R.

where D = specimen diameter; Y = dimensionless factor depending upon the relative crack size.

The relative area $\overline{F}$, depth $\overline{\ell}$ or crack length along the specimen surface $\overline{a}$ may be taken as characteristics of the relative crack size:

$$\overline{F} = \frac{4F}{\pi D^2}, \qquad \overline{\ell} = \frac{\ell}{D}, \qquad \overline{a} = \frac{a}{\pi D}. \tag{4}$$

By solving equations (2), (3), (1) the following expression for Y is obtained:

$$Y = \left[\frac{\pi^2}{2 \cdot 32^2} \cdot \frac{D^5}{L^2} \cdot \frac{E}{(1-\nu^2)} \cdot \frac{d(f/P)}{dF}\right]^{1/2} \tag{5}$$

where L = the distance from the point of force application to the cracked section.

Figure 1 shows the technique for measuring the elastic compliance of the specimen. The crack was observed through microscope 1, the specimen 2 was fixed in the grip 3 and loaded by weights 4. Deflection of the specimen end was measured by a dial indicator 5 accurate to $\pm 10^{-5}$ m. Coolers 6 were used to cool the specimen from 293 to 77 K.

The crack was grown to a certain length by cyclic loading of the specimen, deflection was measured at a given static load, then the crack was grown again and measurements were made again. The measurements were made up to $\overline{a} = 0.6$. On the fracture surface lines were clearly seen corresponding to the crack front location for every static load. The points of crack arrest were consistent with the measurements of crack length made on the specimen surface while it grew. Load was applied below the elastic limit.

Simultaneous measurements of crack length, depth and area made it possible to determine experimentally the relations between their relative values. By using the method of least squares it was possible to approximate the dependence of the relative area upon the relative length:

$$\overline{F} = B_1\overline{a} + B_2\overline{a}^2 \tag{6}$$

of compliance upon area:

$$[(f/P) - (f/P)_o] = B_3F^3 + B_4F^{4/3} \tag{7}$$

of dimensionless factor Y_1 upon the relative area:

$$Y_1 = (B_5\overline{F}^2 + B_6\overline{F}^{1/3})^{1/2} \tag{8}$$

of dimensionless factor Y_2 upon the relative crack length:

$$Y_2 = [(B_7\overline{a} + B_8\overline{a}^2)^2 + (B_9\overline{a} + B_{10}\overline{a}^2)^{1/3}]^{1/2} \tag{9}$$

where B_1 to B_{10} are coefficients determined experimentally.

Analysis of the results shows that the crack shape considerably affects the value of Y_1, and hence the value of K_I.

Analysis of the results shows that the value of Y for all specimens tested is determined singularly by the value of $\overline{a}$ and may be represented by an expression with averaged factors:

$$Y = [(0.4\overline{a} + 2.61\overline{a}^2)^2 + (0.0096\overline{a} + 0.0056\overline{a}^2)^{1/3}]^{1/2}. \tag{10}$$

To evaluate the precision of the technique used to determine fracture toughness, results were obtained with the help of this technique from cylindrical cantilever specimens of steel 1 at 133 K and steel 2 at 153 K at a speed of movement of the force application point of $\approx 0.33 \times 10^{-4}$m/sec. These results were compared with results obtained in eccentric tension of a specimen with a thickness of 0.025 m of steel 1 and 0.013 m of steel 2 at the same temperatures with a speed of grip movement of 0.83×10^{-4}m/sec. Tests in eccentric tension were made in accordance with the requirements of ASTM Standard E 399-74. For cylindrical specimens the calculation was made by using equations (3) and (10).

Figure 2 shows the results obtained, which indicate that the values of K_{Ic} determined by the proposed technique are in good agreement with the values obtained from the tests in eccentric tension. No effect of crack size upon the value of K_{Ic} was observed. This gives substance to the conclusion that in using this method the values of G_{Ic} and K_{Ic} obtained do not depend upon crack shape.

The value of K_{Ic} under cyclic load was determined also from (3) and (10), when the specimen fractured under cyclic load. Figure 3 gives a comparison of numerical values of K for the tested steels obtained under cyclic and static loading of round cantilever specimens in a wide temperature range. The data in Figure 3 show a sharp decrease of values of K_c and K_{Ic} with test temperature. The transition temperature decreases and the value of K_{Ic} increases for cyclic static loading relative to cyclic loading.

CONCLUSIONS

The considerable difference in K values found in plane strain under cyclic and static loading in the heat-resistant steels tested shows that it is necessary to consider the effect of cyclic loading upon the fracture toughness of steels where relevant, and also to carry out further tests in order to study the mechanism of the effect.

REFERENCES

1. 1974 Annual Book of ASTM Standards, Part 10, E 399-74.
2. TROSHCHENKO, V. T. and POKROVSKY, V. V., "Problemy Prochnosty", No. 2, 1973.
3. IRWIN, G. R., "Relation of Stresses near a Crack to the Crack Extension Force", Proc. 9th Int. Congress Appl. Mech., Brussels, 1957.

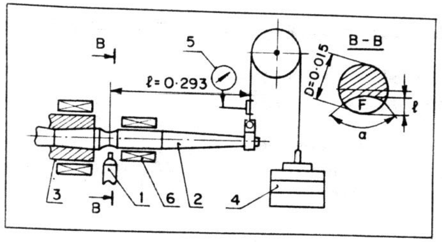

Figure 1 Arrangement for Measuring Elastic Compliance, Dimensions in mm

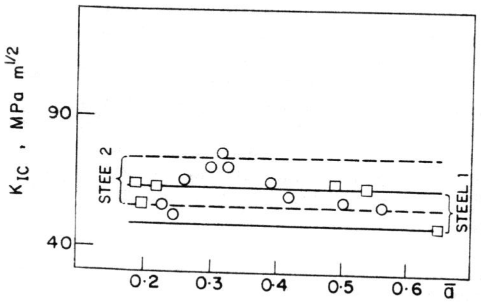

Figure 2 □ - K_{Ic} Values for Steel 1; O - K_{Ic} Values for Steel 2, in Accordance with the Proposed Technique. Lines show the Scatter Band of K_{Ic} Values Obtained by Using the Standard Procedure

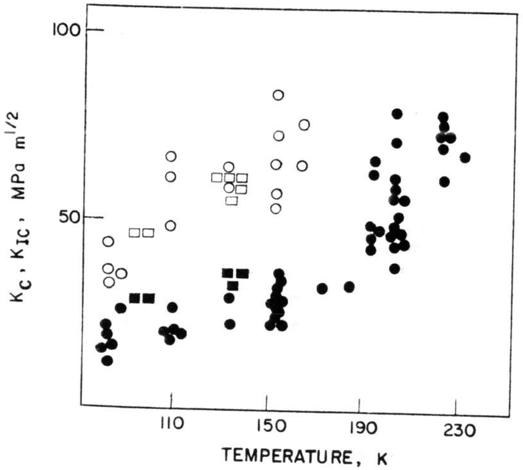

Figure 3 K_{Ic} Values for Steels 1 and 2 Under Cyclic and Static Loading versus Temperature; □ O - K_{Ic} Values for Steels 1 and 2 respectively from Static Loading of Round Cantilever Specimens by the Suggested Technique; ■ ● - the Same Under Cyclic Loading