THE USE OF CHEVRON V-NOTCHED SPECIMENS IN FRACTURE TOUGHNESS DETERMINATION

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ABSTRACT

The relationship between the plane strain fracture toughness, K_{IC}, obtained in accordance with the ASTM E399-78 testing standard and the maximum load, P_{max}, determined from chevron-notched short bar specimens, 3-point bend rectangular specimens and 3-point bend round bar specimens expressed as $K_{IC} = A P_{max}$, where A is a geometric constant, has been investigated. High strength Assab 25X steel of 0.32% C was used. The specimens were tempered from the as-quenched state to 500°C. Although the values of A for a given specimen geometry were found to be roughly constant from 200°C to 400°C, its values at the other tempering temperatures were much larger. Notwithstanding the difference in the geometry of the chevron notch, A for a given heat treatment condition remained essentially invariant for both the 3-point bend specimen geometries throughout the entire range of tempering temperatures studied. However, no relationship could be discerned from the values of A obtained using the short bar and the rectangular bend specimens although both had identical notch geometry. Except at 500°C tempering condition, fracture toughness values calculated for the short bar specimens were found to be generally in good agreement with those obtained from the ASTM test standard when rising crack growth resistance curve was taken into consideration.

KEYWORDS

Plane strain fracture toughness; chevron-notched specimens; crack growth resistance curve; Assab 25X steel.

INTRODUCTION

It has been shown that for brittle materials the relationship between the plane strain fracture toughness, K_{IC}, and the maximum load, P_{max}, determined from a chevron-notched short rod, short bar (Barker, 1978, 1983) or 3-point bend (Shih, 1981) specimens can be expressed as,

$$K_{IC} = A \cdot P_{max} \quad (1)$$

where A is a constant associated with the specific dimensions of the specimen and V-notch. Such relationship is the result of a minimum that occurs in the stress intensity factor per unit load versus crack length curve. Under small scale yielding situation, this minimum is believed to be a constant for a particular specimen geometry. The value of A has been evaluated to be 22.8 for 3-point bend rectangular specimens (Shih, 1981) and to range from 20.8 (Barker, 1977) to 23.9 (Bubsey and others, 1982) for short rod specimens. If A is indeed a constant for a given specimen geometry, the above relationship would be of great usefulness in plane strain fracture toughness determination since the testing of such specimen does not involve fatigue precracking and crack length measurement. Only the maximum load needs to be determined and this can be done accurately and easily.

The present study investigates the possibility of using the above relationship to determine the fracture toughness of Assab 25X, a high strength tool steel using the short bar specimen. To study the effect of specimen geometry, the investigation is extended to include the use of 3-point bend rectangular specimens and 3-point bend round bar specimens. The latter specimen geometry requires the least machining and preparation and hence makes a good specimen for screening test in quality control.

EXPERIMENTAL PROCEDURE

The material used was Assab 25X, a high strength machinable tool steel generally used in bolsters and plastic mould plates. The typical chemical composition was (percentage values): C, 0.32; Cr, 1.00; Mo, 0.20; Mn, 1.00; Si, 0.25 (nearest equivalent, AISI 4130).

Chevron-notched short bar specimens, 3-point bend rectangular and round specimens with dimensions as shown in Figs. 1(a), (b) and (c) respectively and 25 mm thick compact tension specimens of dimensions in accordance with the ASTM standard E399-78 specification were machined from standard plate

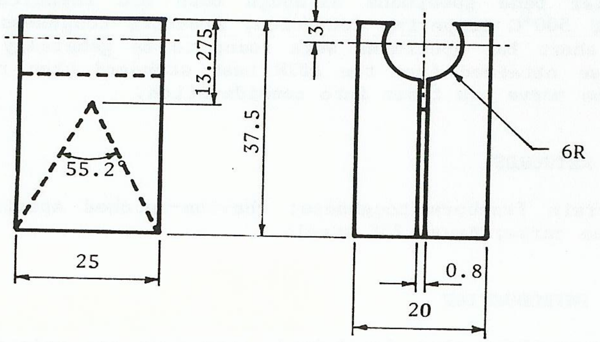

Fig. 1(a). Short bar specimen.

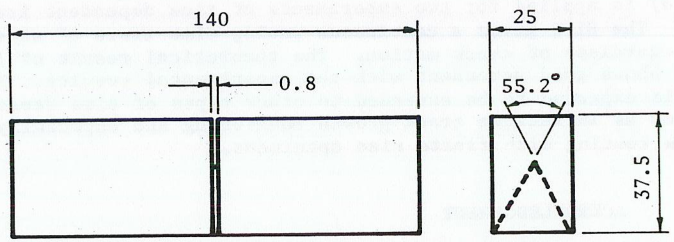

Fig. 1(b). 3-point bend rectangular specimen.

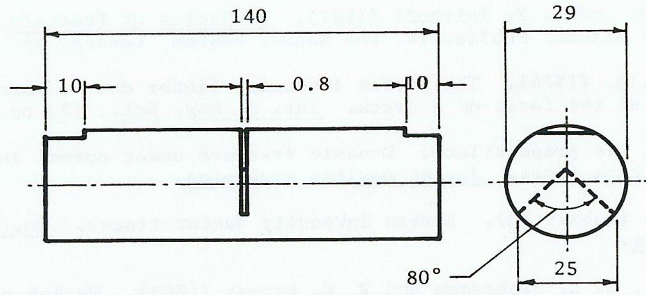

Fig. 1(c). 3-point bend round bar specimen.

stock of 28.5 mm thickness. The various dimensions used in the short bar specimens were of proportions similar to those suggested by Barker (1979). The geometry of the chevron notch was identical in the short bar and the 3-point bend rectangular specimens in that both had a secant angle of 55.2°, whereas an angle of 80° was used in the 3-point bend round specimens. A crack plane in the T-L orientation was chosen for the four mentioned specimen geometries. All test specimens were austenitized at 850°C for an hour and then quenched in oil. Apart from the as-quenched specimens, all other specimens were tempered for one hour at each of the following temperatures: 200, 300, 400 and 500°C. At least three specimens of each geometry were tested at each tempering temperature.

Compact tension specimens were fatigue precracked using an Instron electromagnetic resonance machine with stress intensity in the range specified by the ASTM standard. During the fracture test, the displacements were measured using a standard double-cantilever beam clip gauge fixed onto the specimen by means by attachable knife-edges. Load and displacement outputs were recorded on an X-Y recorder.

The fracture test for the chevron-notched short bar specimens was performed using a pair of grips shown in Fig. 2. The specimen was aligned so that the sample face at the machined notch coincided with the axis of applied

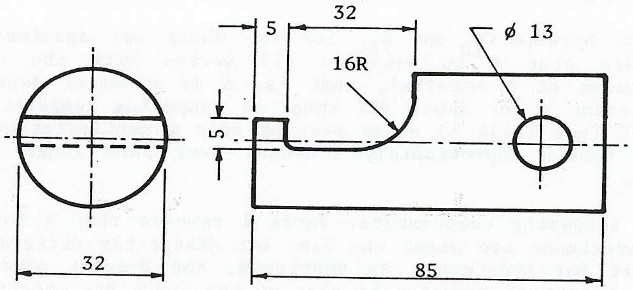

Fig. 2. Loading fixture for short bar specimen.

load. The 3-point bend specimens were fracture tested with a test rig of span 130 mm. A constant cross-head speed of 0.5 mm/min was used for all the chevron-notched specimens.

The 0.2% proof stress of the material was obtained from tensile specimens machined from the fractured compact tension specimens with the axis of the test specimen perpendicular to the crack plane of the compact tension specimen. Generally, two tensile specimens were tested at each tempering temperature.

RESULTS AND DISCUSSION

Figure 3 shows the variation of the average plane strain fracture toughness, K_{IC}, and the 0.2% proof stress, σ_y, of Assab 25X with tempering temperature. The K_{IC} values were reproducible within a scatter of less than 6%. The shape of the K_{IC} curve is similar to those observed commonly (Lai and Ferguson, 1980; King, Smith and Knott, 1977; Schwalbe and Backfish, 1977), with a distinct drop in fracture toughness value at a tempering temperature of about 350°C indicating the occurence of tempered martensite embrittlement. At 400°C and above, the toughness was found to increase rapidly with tempering temperature. With P_{max}/P_Q and $2.5\ (K_{IC}/\sigma_y)^2$ of less than 1.08 and 19 mm respectively, the fracture toughness values for the material were all considered in accordance to the ASTM standard to be valid K_{IC} values. Shear lips of sizes ranging from 0.2 mm (1.6% of specimen thickness) in the as-quenched state to 2.5 mm (10%) in the 500°C tempered condition were observed in the fractured compact tension specimens.

The values of A in equation (1) for the short bar, 3-point bend rectangular and round specimens are summarised in Table 1. It can be seen that for all specimen geometries, the values of A range from 1.38 to 4.84. These values are not in agreement with those obtained by Shih (1981) and Barker (1977) even when non-dimensionalised with $B^{3/2}$ or B/W where B and W are respectively the thickness and the width of the specimens. Moreover, Table 1 shows that though A generally remains roughly constant between tempering

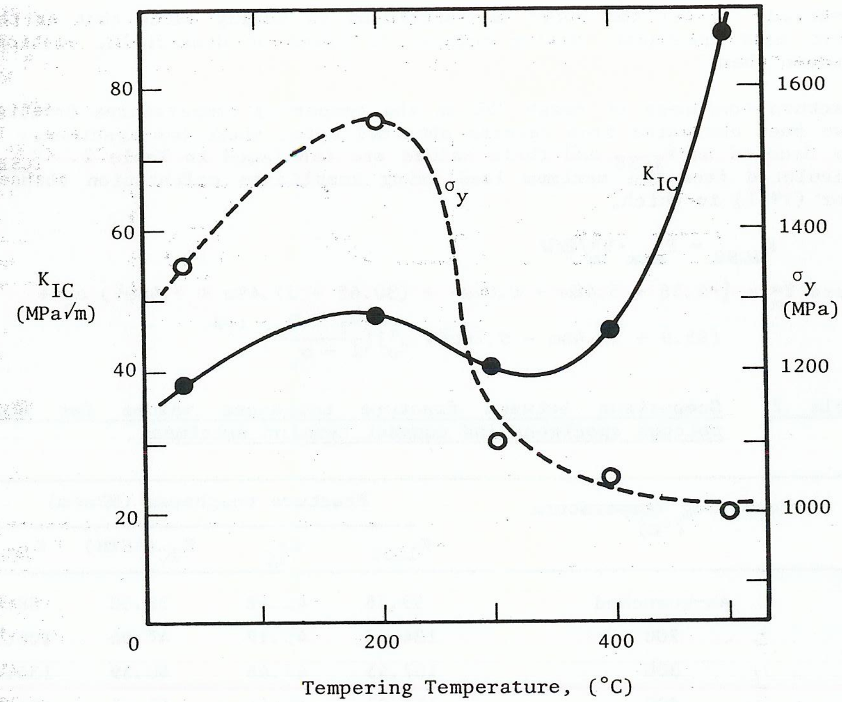

Fig. 3. Variation of K_{IC} and σ_y with tempering temperature.

Table 1 Average values of A for different specimen geometries having different tempering temperatures

Tempering Temperature °C	Specimen Geometry: Short bar	3-point bend rectangular	3-point bend round
As-quenched	4.84	1.84	2.19
200	2.69	1.88	1.85
300	2.54	1.38	1.42
400	2.74	1.53	1.50
500	3.90	2.60	2.48

temperatures 200 and 400°C, its values are slightly higher at other heat treatment conditions. For a given tempering temperature, only a small variation in A between the two 3-point bend specimen geometries is observed. A for the short bar specimens is nearly twice that for the 3-point bend specimens, having however no fixed or discernible relationship between them.

Fracture toughness of Assab 25X at the tempering temperatures investigated have been estimated from results obtained using short bar specimens. These are denoted as K_{ICSB} and their values are tabulated in Table 2. K_{ICSB} was calculated from the maximum load using compliance calibration obtained by Munz (1981) in which,

$$K_{ICSB} = P_{max} \cdot Y_m^*/B\sqrt{W} \quad (2)$$

where $Y_m^* = \{-0.36 + 5.48\omega + 0.08\omega^2 + (30.65 - 27.49\omega + 7.46\omega^2)\alpha_o + (65.9 + 18.44\omega - 9.76\omega^2)\alpha_o^2\}\left(\frac{\alpha_1 - \alpha_o}{1 - \alpha_o}\right)^{1/2}$

Table 2 Comparison between fracture toughness values for chevron-notched specimens and compact tension specimens

Tempering Temperature (°C)	Fracture toughness (MPa√m)			
	K_{ICSB}	K^*_{IC}	K_{IC}(ASTM)	K_{ICRT}
As-quenched	53.78	42.68	38.68	88.63
200	124.77	45.17	47.96	106.57
300	107.45	47.46	40.39	135.41
400	112.07	47.41	45.67	126.09
500	150.02	28.17	87.05	141.39

For the specimens used in the present investigation, ω = 3.75, α_o = 0.354 and α_1 = 1. Equation (2) yields K_{ICSB} values very similar to those obtained by using the $K_{ICSB} - P_{max}$ relationship suggested by Shannon and others (1981). It is evident from Table 2 that K_{ICSB} values grossly overestimate the plane strain fracture toughness, K_{IC}, values. This overestimation is consistent with the finding of Munz (1981) who attributed it to be the result of rising crack growth resistance curve. The shear lip formation in the Assab 25X specimens although small is an indication that the material has a rising crack growth resistance curve. In order to better estimate the K_{IC} values, rising crack growth resistance has to be accounted for in the estimation. This is done by using the $K_{ICSB} - K_{IC}$ relationship proposed by Munz (1981). The resulting fracture toughness is denoted as K^*_{IC} and the corresponding values are given in Table 2. It can be observed from the table that for K_{IC} < 50 MPa√m, that is, between as-quenched and tempering temperature 400°C, K^*_{IC} values are in good agreement with the K_{IC} values obtained with compact tension specimens, even though the values of A are seen to be changing. At 500°C tempering condition, the value of K_{IC} is 87.05 MPa√m which is outside the applicability of Munz's $K_{ICSB} - K_{IC}$ relationship and hence, K^*_{IC} is not expected to give an accurate K_{IC} value.

Fracture toughness values were also estimated using results from the 3-point bend rectangular specimens and the corresponding K-calibration (Munz and others, 1981). These, denoted by K_{ICRT}, are tabulated in Table 2. K_{ICRT}, like K_{ICSB}, overestimates K_{IC} as much as 3.4 times. Unfortunately, a better estimation by accounting for the rising crack growth resistance cannot be performed as $K_{ICRT} - K_{IC}$ relationship similar to that used for short bar specimens above is not available.

The agreement between K^*_{IC} and K_{IC} for the short bar specimens discussed above suggests that A in equation (1) varies with the crack growth resistance curve of a material, that is, A is material dependent. The apparent constant A for Assab 25X steel at tempering temperatures between 200 and 400°C (see Table 1) seems perhaps only a manifestation of the K_{IC} values that remain approximately constant over this range of tempering temperatures.

For a given tempering temperature, Table 1 reveals that A for the two 3-point bend specimens are about the same but distinctly different from that for the short bar specimen. As mentioned, the 3-point bend rectangular specimen has identical geometry to that of the short bar specimen with only a difference in the mode of loading. On the other hand, the geometry of the chevron notch and the specimen as a whole for the two 3-point bend specimens are dissimilar. Consequently, within experimental inaccuracy, it can be observed that A is more sensitive to the change in the mode of loading rather than to the geometry of the specimen and its chevron notch.

Gauging from the results obtained in the present study, it is evident that A may not be a unique constant. To use it in fracture toughness determination of a material, A for a given specimen geometry has to be first evaluated using ASTM standard test. This therefore restricts the applicability of equation (1). However, for the 3-point bend round bar specimens, the reproducibility of A for a given heat treatment condition is good, with experimental scatter of less than 6%. This consistency, couples with the ease in specimen fabrication and testing, makes the 3-point bend round bar specimen suitable for screening test in quality control.

CONCLUSION

1. The value of A in the $K_{IC} - P_{max}$ relationship is found to vary with tempering temperature even when a fixed specimen geometry is used, indicating that A is material dependent.

2. From comparison between the three types of specimen geometries investigated, A is seen to be more sensitive to the change in the loading mode and less to the variation in specimen geometry.

3. Fracture toughness of Assab 25X calculated using maximum load obtained in the chevron-notched short bar specimen and its corresponding K-calibration overestimates the plane strain fracture toughness value. However, when rising crack growth resistance curve is taken into consideration, a good estimation of K_{IC} can be achieved.

4. The 3-point bend chevron-notched round bar specimen may be usable in quality control purposes in that the value of A at a given heat treatment condition is reproducible within an experimental scatter of less than 6%.

REFERENCES

Barker, L.M. (1977). Engineering Fracture Mechanics, 9, 361 - 369.
Barker, L.M. (1978). Fracture Mechanics of Ceramics, 3, 483 - 494.
Barker, L.M. (1979). ASTM STP 678, 73 - 82.
Barker, L.M. (1983). Engineering Fracture Mechanics, 17, 289 - 312.
Bubsey, R.T., Munz, D., Pierce, W.S. and Shannon, Jr., J.L. (1982). International Journal of Fracture, 18, 125 - 132.
King, J.E., Smith, R.F. and Knott, J.F. (1977). 4th International Conference on Fracture, Canada, 2A, 279 -286.
Lai, M.O. and Ferguson, W.G. (1980). Engineering Fracture Mechanics, 13, 285 - 292.
Munz, D. (1981). Engineering Fracture Mechanics, 15, 231 - 236.
Munz, D., Himsolt, G. and Eschweiler, J. (1981). ASTM STP 745, 69 - 84.
Schwalbe, K.H. and Backfish, W. (1977). 4th International Conference on Fracture, Canada, 2A, 73 - 78.
Shannon, Jr., J.L., Bubsey, R.T., Munz, D. and Pierce, W.S. (1981). 5th International Conference on Fracture, France, 1127 - 1141.
Shih, T.T. (1981). Journal of Testing and Evaluation, 9, 50 - 55.