Fracture 1977, Volume 2, ICF4, Waterloo, Canada, June 19 - 24, 1977

SHORT ROD K_{Ic} TESTS OF SEVERAL STEELS AT TEMPERATURES TO 700K

L. M. Barker* and W. C. Leslie**

INTRODUCTION

A programme is under way at Terra Tek to develop a drill bit capable of sustained operation at the temperatures encountered in drilling geothermal wells. The problem involves the reoptimization of conventional oil well tricone roller drill bits by using new drill-bit steels which have better hot hardness performance, and therefore better high-temperature wear characteristics. However, the new steels must also have sufficient toughness in the operating temperature range to withstand the heavy drilling loads without fracturing. This paper presents the fracture toughness measurements made on several steels as part of the programme to develop an improved geothermal drill bit. Four steels are reported: (1) Vasco MA, an ultra-high-strength steel; (2) H 13, a high temperature tool steel; (3) M 50, a high temperature bearing steel; and (4) S 2, a tool steel used for bearings in oil well drill bits. As far as is known, these fracture toughness values are the first to be published for these materials. The plane strain critical stress intensity factor, K_{Ic}, was measured by the recently-developed short rod technique [1, 2]. The short rod specimen configuration was particularly well adapted to the tests of the two drill-bit bearing steels, inasmuch as the specimens were made with a minimum of machining from actual drill-bit roller bearings. In addition, the small sample size made it easy to attain the desired uniform temperatures, and the absence of fatigue pre-cracking with the technique further simplified the K_{Ic} measurements. The short rod technique is described in the next section, which includes a short theoretical development which supplements those of references [1] and [2]. The results of K_{Ic} tests of this paper are then presented and discussed.

TEST DESCRIPTION AND THEORY

The specimen configuration is the longitudinally pre-slotted short rod of Figure 1, and a test is performed by slowly increasing the load, P, on the specimen. At some point, a crack initiates at the point of the "V", and the crack growth is initially stable. The load necessary to advance the crack increases until the crack reaches a critical length, a_c; thereafter, the load decreases with increasing crack length. The peak load, P_c, during the experiment is used in a simple equation to calculate K_{Ic}.

The equation for K_{Ic} is derived from linear elastic fracture mechanics principles, assuming that the energy per unit area of new crack surface created in plane strain is a material constant, G_{Ic}. Under plane strain conditions, then, the energy required to advance the crack a small distance, da (Figure 2a), is

* Terra Tek, Inc., 420 Wakara Way, Salt Lake City, Utah 84108, U. S. A.
** University of Michigan, Ann Arbor, Michigan 48103, U. S. A.

$$dW_1 = G_{Ic}\ b\ da\ , \qquad (1)$$

where b is the width of the crack front. The energy, dW_1, comes from the irrecoverable work done on the specimen during the test, as shown below.

To initiate the crack, one loads the specimen with a force P, causing the front of the specimen to open by an amount x (Figure 2b). Before initiation, the loading path (P vs. x) proceeds up a steep linear elastic slope as depicted in Figure 2c. The onset of nonlinearity in the loading path signifies the initiation of the crack at the point of the "V".

Suppose that the force is continually increased until the crack length, a, and the load point opening, x, are as shown in Figure 2b; and the loading path is at A in Figure 2c. If the sample were unloaded from that point, the unloading path would be a straight line to the origin, since no plastic work and no crack growth occur on unloading. The irrecoverable work done on the specimen during the loading-unloading cycle would be the area 1 of Figure 2c, i.e., the area between the loading and unloading paths.

Now suppose that instead of unloading from point A, the crack is advanced an additional increment, da, which would be accompanied by an additional load-point-opening increment, dx, such that the loading path would advance to point B. A subsequent unloading from B would again produce a straight line to the origin (Figure 2c). It is clear that *the additional irrecoverable work, dW_2,* done in advancing the crack the additional distance, da, is given by the shaded area of the triangle OAB, or

$$dW_2 = \frac{1}{2}\ Pdx\ . \qquad (2)$$

From the definition of the elastic compliance of the specimen, c = x/P, and letting P be the average value of the load (i.e., a constant) during the crack advance, da, we have dx = Pdc, or

$$dW_2 = \frac{1}{2}\ P^2 dc\ . \qquad (3)$$

According to the Griffith-Irwin-Orowan criterion, dW_2 represents a release of strain energy by the specimen which is available for creation of the new crack area. Thus, equating dW_1 (equation 1) and dW_2, we obtain

$$G_{Ic} b = \frac{P^2}{2}\ \left\{\frac{dc}{da}\right\}\ . \qquad (4)$$

Here, b, P and dc/da are evaluated at the crack length, a, at which the incremental crack advance took place. Equation (4) is not new; essentially the same equation was published by Irwin and Kies [3] in 1954. It was re-derived here simply to show its applicability to our specimen configuration.

In order to cast equation (4) in terms of the critical stress intensity factor, K_{Ic}, the plane strain equation relating G_{Ic} and K_{Ic} is used:

$$G_{Ic} = K_{Ic}^{\ 2}\ (1-\nu^2)/E\ . \qquad (5)$$

Thus, equation (4) becomes, after some manipulation,

$$K_{Ic} = \frac{P}{B^{3/2}\ (1-\nu^2)^{1/2}} f(a/B)\ , \qquad (6)$$

where B is the specimen diameter, and where

$$f(a/B) = \left[\frac{B\ \ d(cEB)}{2b\ \ d(a/B)}\right]^{1/2}\ . \qquad (7)$$

The quantity in brackets is a function only of the ratio a/B, independent of the specimen material, as long as the scaled specimen configuration remains constant. Therefore, as with other fracture toughness specimen geometries, this geometry can be carefully compliance calibrated, and f(a/B) can be approximated by a polynomial in a/B. Once the coefficients in f(a/B) are evaluated, a K_{Ic} measurement can be made by advancing a crack to some measured value of a [so that f(a/B) can be evaluated] and then measuring P necessary to further advance the crack.

The development of equation (6) has closely paralleled the development of equations for K_{Ic} using standard ASTM specimens. At this point, however, a significant simplification can be made in the case of the short rod test, for it has been shown [1] that the scaled crack position, a_c/B, at which the peak load is encountered is again *independent of the specimen material*, being a function only of the specimen geometry. Thus, the value of f(a/B) in equation (7) at the time of the maximum load, P_c, is a constant, A = f(a_c/F). Therefore, we have

$$K_{Ic} = AP_c/[B^{3/2}\ (1-\nu^2)^{1/2}]\ , \qquad (8)$$

or simply

$$K_{Ic} = AP_c/B^{3/2}\ , \qquad (9)$$

if we follow custom in replacing $(1-\nu^2)^{1/2}$ by unity.

Equations (8) and (9) are simplified compared to the ASTM formula for K_{Ic} by the replacement of a fourth-order polynomial by the dimensionless constant, A. In addition, no measurement of crack length is required, and rather than determining P from the intersection of a 5 percent slope offset line with the load-displacement curve [4], P is simply the maximum load during the experiment, P_c. Fatigue pre-cracking of the short rod specimen is generally not necessary.

DATA AND RESULTS

The nominal compositions of the tool steels tested are given in Table 1. The thermal history, grain size, and some mechanical properties are shown in Table 2. The microstructure of all four steels was tempered martensite with undissolved carbides. The number of the latter varied with carbon content. The samples were prepared as follows.

Vasco MA: Specimen blanks 12.7 mm diameter by 19 mm long were cut from a forging 105 mm diameter by 90 mm long, using stock close to the periphery of the forging. The sample axes were parallel to the axis of the forging. The samples were then heat treated (Table 2), after which the slots were ground.

H 13: Specimens 12.7 mm diameter by 19 mm long were cut from a drill bit lug forging which had been heat treated as indicated in Table 2. The sample axes were parallel to the elongated axis of the rather irregular forged shape.

M 50: Roller bearings were made from hot rolled stock, with the heat treatment indicated in Table 2. Specimens of 10.1 mm diameter by 15.2 mm long were then made, using the full diameter of the roller bearings. The crack orientation was C - L [4].

S 2: Same as M 50, except specimens were 12.7 mm diameter by 19 mm long.

The measured fracture toughness data are plotted in Figure 3.

The ten measurements on Vasco MA show very little scatter at any temperature. However, duplicate measurements at 590K showed much more scatter for both H 13 and M 50. No attempt was made to keep the crack orientation exactly the same between the H 13 samples cut from the drill bit forging; this may account for some of the data scatter. However, the difference between the M 50 data points at 590K is also much larger than normal for the short rod technique, and remains unexplained at present.

Fracture toughness specimens must satisfy certain minimum size requirements in order to yield valid measurements of K_{Ic}. In the case of ASTM standard specimens, the thickness and the crack length must each exceed $2.5(K_{Ic}/\sigma_y)^2$ [4], which is about fifty times the plastic zone size. The minimum specimen diameter for a valid K_{Ic} measurement with the short rod configuration has not yet been accurately determined. However, for two kinds of aluminum, it has been shown that a specimen diameter of $4.6 (K_{Ic}/\sigma_y)^2$ was certainly large enough* [2]. Similarly, in recent experiments on AISI 4820, a diameter of $4.2(K_{Ic}/\sigma_y)^2$ gave size-independent results*. For the experiments of this paper, the sample diameters were always greater than $4.8(K_{Ic}/\sigma_y)^2$; thus; the K_{Ic}'s of Figure 3 should be free of size effects.

The K_{Ic} measurements presented here have contributed to the understanding of full scale laboratory tests of research drill bits under simulated geothermal drilling conditions. Further measurements on other steels are being conducted to assure sufficient fracture resistance when the first advanced geothermal drill bits are field tested.

* No experiments were done on smaller diameters.

ACKNOWLEDGEMENT

This work was partially supported by the U. S. Energy Research and Development Administration, Division of Geothermal Energy, with Mr. Cliff Carwile as contract monitor.

REFERENCES

1. BARKER, L. M., "A Simplified Method for Measuring Plane Strain Fracture Toughness", accepted for publication in Eng. Fract. Mech.
2. BARKER, L. M., Proceedings of the ICM-II Conference, Boston, 1976, 1547.
3. IRWIN, G. . and KIES, J. E., Weld. J., 33, 1954, 193.
4. ASTM: E399-74, Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials.

Table 1 Nominal Steel Composition

Steel	Composition (%)						
	C	Cr	Mm	Mo	Si	V	W
Vasco MA	.51	4.5		2.75	.22	1.0	2.0
H 13	.35	5.0	.4	1.5	1.0	1.0	
M 50	.8	4.1	.3	4.25	.2	1.0	
S 2	.5		.4	.5	1.0		

Table 2 Heat Treatments and Properties

Steel	(a)	Quench	Temper	(b)	(c)	Yield (GPa)	Elongation (%)
Vasco MA	1115	Salt	525°C, 2+2+2 hr.	8-9	59	2.01	6
H 13	995	Air	540°C, 2+2 hr.	8-9	54	1.64	9
M 50	1120	Salt	525°C, 2+2 hr.	6-7	64	2.33	1.6
S 2	860	Oil	190°C, 1 hr.	9-10	57	2.15	2

(a) Austenitizing temperature, °C.
(b) Austenite grain size (ASTM)
(c) Hardness (Rockwell C)

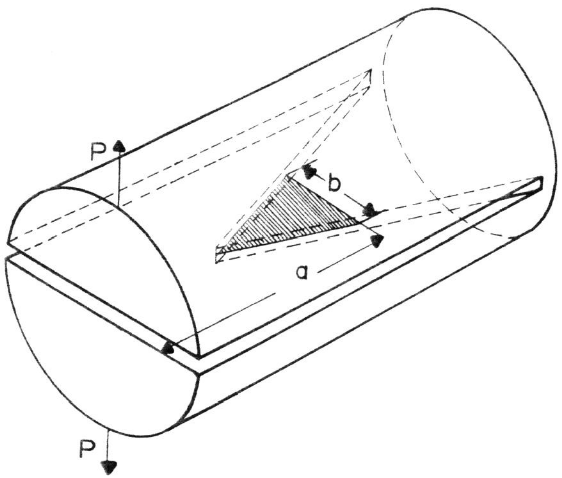

Figure 1 Short Rod Specimen Configuration. The Shaded Area Denotes the Crack

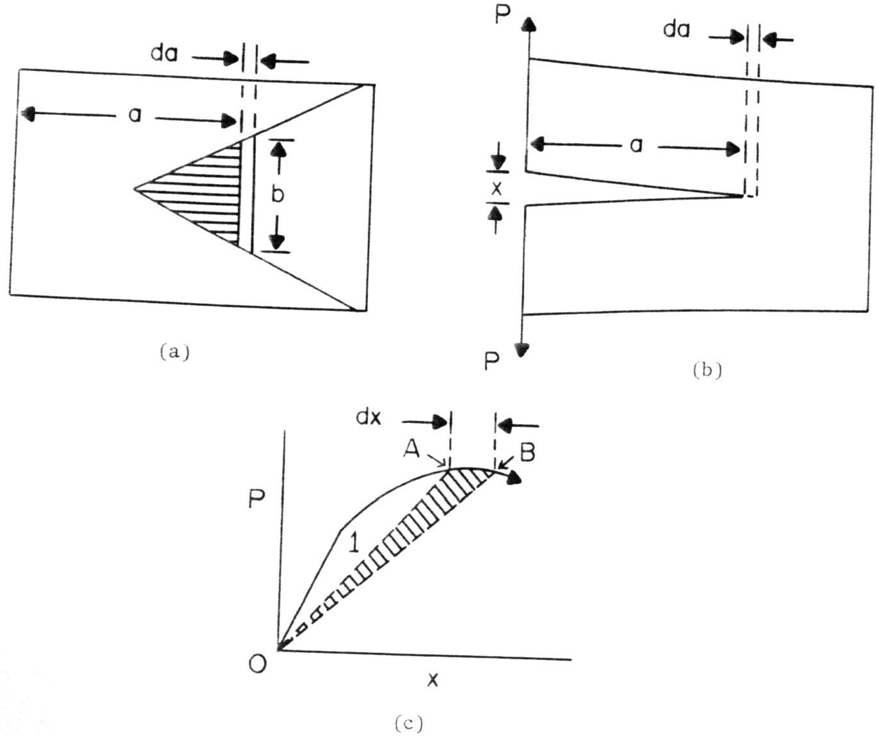

Figure 2 (a) Plan View of Specimen with Crack Advance Increment, da
(b) Side View of Specimen
(c) Load versus Load-Point-Opening Paths

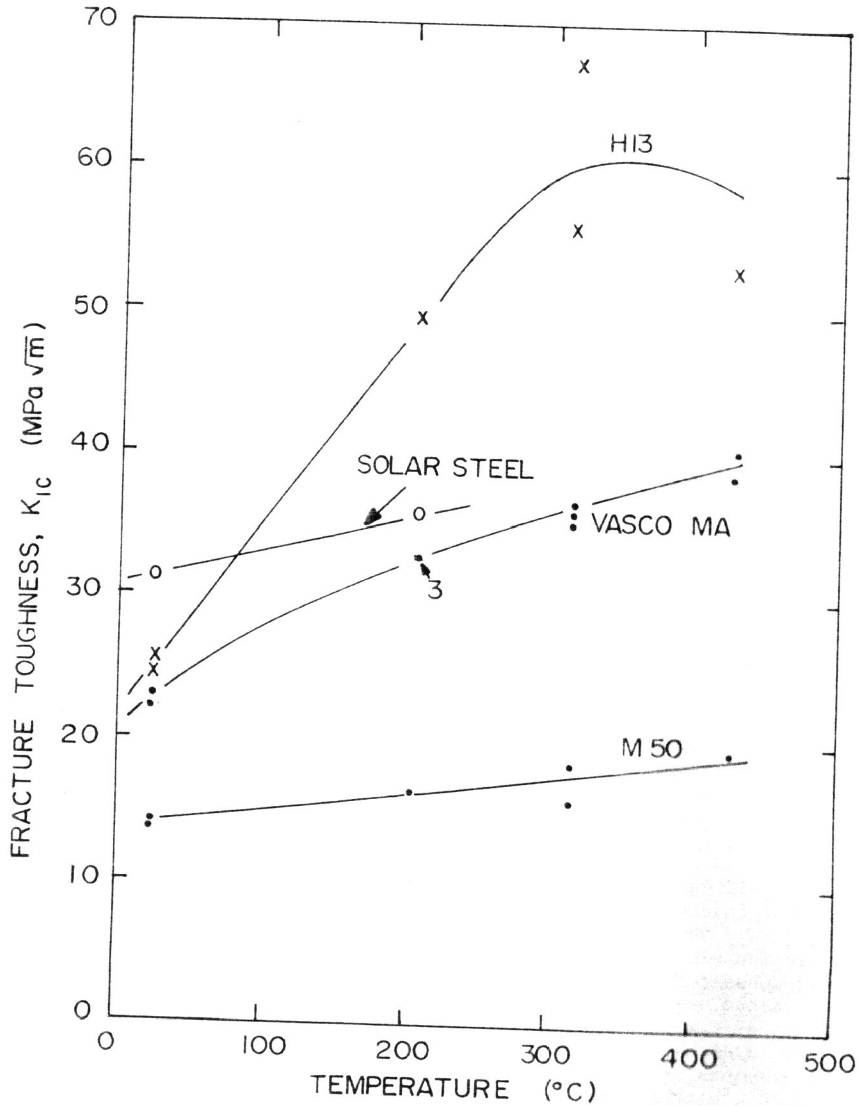

Figure 3 Temperature Dependence of K_{Ic}