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FRACTURE TOUGHNESS OF TURBINE ROTOR SHAFT AND VALIDITY CRITERION FOR K_{IC}

K. Ikeda*, M. Aoki*, H. Kikuchi**
U. Schieferstein*** and C. Berger***

INTRODUCTION

According to the ASTM validity criteria for the plane strain fracture toughness, K_{IC}, the measured fracture toughness should satisfy the following conditions [1]: (i) the specimen geometry validity, a and B $\geq 2.5 \times (K_Q/\sigma_y)^2$, (ii) the load-displacement curve validity, $P_{max} < 1.1\ P_Q$. The limited section of material taken from various components of structures often makes the thickness criterion a difficult one to meet. In this paper, very large disc type specimens of 345 mm thick and 920 mm dia. prepared from low-pressure turbine rotor shafts were tested to evaluate the valid fracture toughness.

In addition, the validity criterion for K_{IC} has been investigated by using various sizes of compact tension specimens, and proposed as $P_{max}=P_Q$.

MATERIALS AND TESTING PROCEDURES

The materials tested are 2.8Ni-Cr-Mo-V steels for low pressure turbine rotor and the three discs were prepared from prolongated parts of rotor shafts manufactured by Kobe Steel, Ltd. as shown in Figure 1. The chemical composition, quality heat treatment and mechanical properties of the three discs are presented in Tables 1 through 3. The two rotor and prolongation test forgings were heat treated as one solid piece each.

After the 14 RCT specimens (Round Compact Tension specimen of 14 inch thick) [2] shown in Figure 2, which had the original diameter of the prolongated forgings, were tested, various sizes of smaller CT specimens (Compact Tension specimen) were taken from the central and mid-thickness portions of the 14 RCT specimens.

To our best knowledge, the 14 RCT specimens used for this investigation are the largest fracture toughness specimens ever tested in this world. The smaller specimens were of the sizes 1, 3 and 6 CT/ASTM-E399 [1].

A fatigue testing machine of large load capacity is needed to precrack the tip of the machined chevron notch of 14 RCT specimen. Indeed, the fatigue precracking of 14 RCT specimen was carried out at the cyclic rate of 1 Hertz and the cyclic load of 0-1,500 kN which was produced by the combination of the ± 600 kN servo-hydraulic testing machine and the load-amplifying clevis shown in Figure 3, in which the principles of lever are utilized. The pins, D, in Figure 3 are located at both surfaces of

*Structural Engineering Laboratory, Kobe Steel, Ltd., Japan.
**Steel Casting & Forging Division, Kobe Steel, Ltd., Japan.
***Materials Engineering and Research Division, Kraftwerk Union AG., Muelheim/Ruhr, West Germany.

the 14 RCT specimen and play a role of fulcrum subjected to compression. The supporting bed, S, whose surface has the larger radius of curvature than that of the 14 RCT specimen, may convert the horizontal displacement of RCT specimen due to loading into a rotational one with minimum friction. It takes about 300×10^3 cycles to precrack by about 10 mm at the tip of a machined chevron notch on the surface of RCT specimen. The fracture tests of the precracked RCT specimen were conducted by using a 30,000 kN tensile testing machine.

The precracking and fracture testing of the smaller-sized CT specimens was conducted by using a ± 600 kN servo-hydraulic and a 3,000 kN tensile testing machine, respectively.

The load as a function of clip gage displacement at the edge of notch was plotted by using an X-Y recorder. The fatigue precracking and the measurement of the crack lengths after fracture were carried out according to ASTM-E399.

The measured fracture toughness, K_Q, is said to be a valid one, K_{IC}, if the following requirements are met:

$$a \text{ and } B \geq 2.5(K_Q/\sigma_Y)^2 \tag{1}$$

$$P_{max} < 1.10\ P_5 \tag{2}$$

where

- a: crack length,
- σ_Y: yield stress,
- B: specimen thickness,
- P_{max}: fracture load,
- P_5: load at which the secant drawn on the load-displacement record at a slope 5% less than that of the load-displacement curve at the origin, cuts. (see Figure 4)

In general, three different types of load-displacement curves are produced as shown in Figure 4. The requirement of equation (2) is met for the curves of Figures 4(a) and 4(b). The following requirement of equation (3) proposed in this paper which is more conservative than that of equation (2), is met only for the curve where P_{max} occurred before P_5 as shown in Figure 4(a), however, this does not necessarily guarantee geometric validity, equation (1).

$$P_{max} = P_Q \tag{3}$$

The testing temperature of the smaller CT specimens taken from the fractured 14 RCT ones was determined so as to satisfy all the following three conditions independently of specimens A, B and C: (i) In case of 6 CT test, both the requirements of equations (1) and (3) are met. (ii) In case of 3 CT test, the requirement of equation (1) is not met but that of equation (3) is met. (iii) In case of 1 CT test, neither the requirement of equation (1) nor equation (3) is met.

TEST RESULTS AND DISCUSSION

CT test

The effects of specimen thickness on fracture toughness from various sizes of CT test specimen are shown in Figure 5. The thickness of CT specimen means the size of that. The load-displacement records are shown in Figure 6. K_Q value from 6 CT test is said to be a valid estimate of K_{IC}, because both the requirements of equations (1) and (3) are met. K_Q from 3 CT test does not satisfy equation (1) but equation (3), however, that value is found to be nearly equal to the K_{IC} value from the 6 CT test. K_Q from 1 CT satisfies neither equation (1) nor equation (3), and that value is always smaller than K_{IC} value.

Therefore, valid K_{IC}-values may well be measured even if the specimen geometry requirement, equation (1), is not fulfilled. The important point is that fracture occurs within the elastic region, that is, within the linear part of the load-displacement curve.

Then, it is concluded that "invalid" fracture toughness value, K_Q, can be regarded as a valid one, K_{IC}, as long as the requirement of equation (3) is met. K^W_{IC} in Figure 5 is the predicted K_{IC} value from "invalid" test by employing the equivalent energy method suggested by Witt and Mager [3] and K^C_{IC} by the application of the Bilby-Cottrell-Swinden model [4] to CT test as proposed by Chell et al. [5].

Where the linearity of load-displacement curve is approximately kept to the point of fracture as in the 3 CT test, the values of K^W_{IC} and K^C_{IC} are nearly equal to that of K_{IC}. However, where the requirement of equation (3) is not met as in the 1 CT test, the values of K^W_{IC} and K^C_{IC} are considerably different from that of K_{IC}.

14 RCT test

At first, the loading on specimen B of 14 RCT was carried out at 10°C. The load-displacement record is shown in Figure 7. Fracture did not occur after P_Q in Figure 7. Then, the fracture tests of specimens A and C of 14 RCT were conducted at -20°C and -30°C, respectively. K_Q from RCT test is calculated from the equation (2):

$$K_Q = P_Q / (B \cdot W) \cdot \sqrt{a}\ F(a/W) \tag{4}$$

$$F(a/W) = 29.6 - 162\ (a/W) + 492.6\ (a/W)^2 - 663.4\ (a/W)^3 + 405.6\ (a/W)^4 \tag{5}$$

where W is the specimen width.

K_Q from specimen A does not satisfy the requirement for "a" of equation (1) but for "B". However, this K_Q value can be regarded as K_{IC}, because the requirement of equation (3) is met. K_Q from specimens B and C are not regarded as K_{IC}, because the requirement of equation (3) is not met. Material for specimen C shows higher toughness than that for specimens A and B. K_{IC} values obtained from 14 RCT, 6 CT and 3 CT tests are shown in Figure 8 as a function of temperature in comparing with available K_{IC}-data points from 2.8Ni-Cr-Mo-V rotor forgings [6,7]. For reference K_Q from the 14 RCT tests are also shown in this figure. It is noted in Figure 8

that the fracture toughness of forgings tested are at the upper bound of the scatterband established by the tests with specimens from other rotor forgings.

CONCLUSIONS

The invalid fracture toughness K_Q according to ASTM specification can be regarded as the valid one, K_{IC}, so long as the approximate linearity of load-displacement curve, $P_{max}=P_Q$, is kept to the point of fracture.

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Table 1 Chemical composition of test material

Specimen	Chemical Compositions, % [1]												
	C	Si	Mn	P	S	Cr	Mo	Ni	V	As	Cu	Sb	Sn
A	0.27	0.07	0.32	0.007	0.009	1.49	0.34	2.86	0.08	0.003	0.02	0.0039	0.003
B													
C	0.28	0.03	0.29	0.008	0.009	1.66	0.35	2.94	0.10	0.002	0.02	0.0014	0.002

1) heat analysis, average value

Table 2 Quality heat treatment of test material

Specimen	Quality heat treatment
A + B	830°C 35h / water spray quench + 630°C 66h / controlled furnace cool
C	850°C 35h / water spray quench + 830°C 35h / water spray quench + 630°C 40h / controlled furnace cool

Table 3 Mechanical properties of test material

Specimen [1]	$\sigma_{0.2}$ N/mm²	σ_B N/mm²	Elong. %	R.A. %	Number of tests
A + B	629~679	758~882	13~20	54~62	14
					21
C	680~720	802~861	17~21	58~64	14
					16

1) Specimen orientation and distribution : radial over total cross-section of 920 mm dia-prolongation forging.

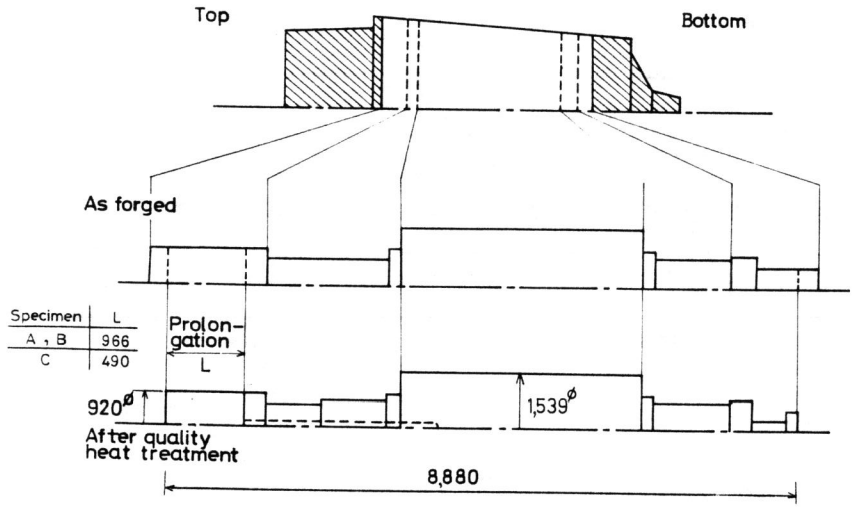

Figure 1 Relative position of rotor and prolongation test forging in the 150 ton ingot and the 85 ton forging

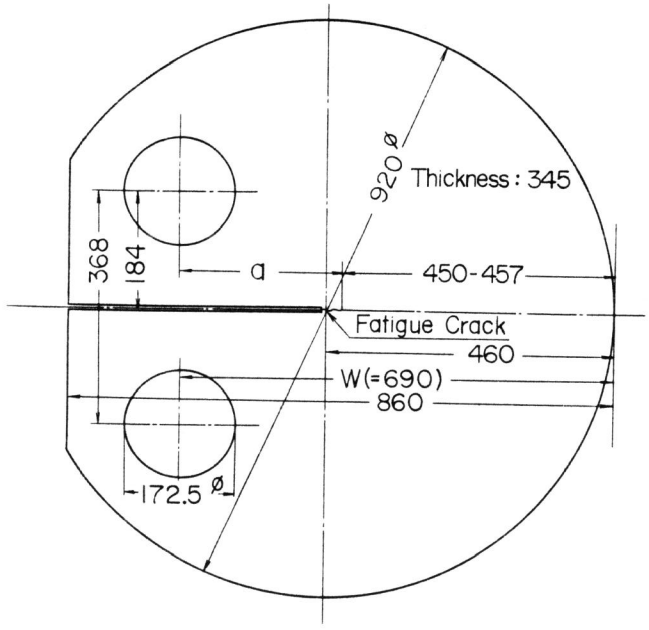

Figure 2 14 RCT specimen [2]

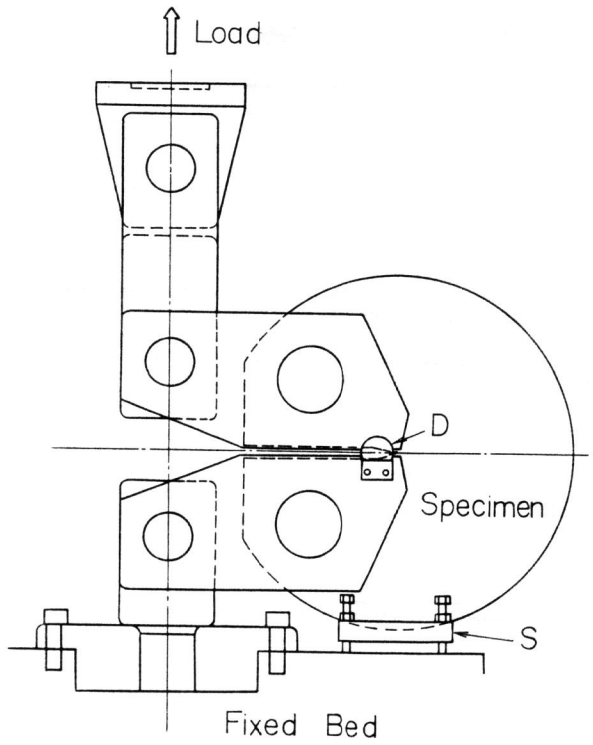

Figure 3 Clevis for fatigue cracking of 14 RCT specimen

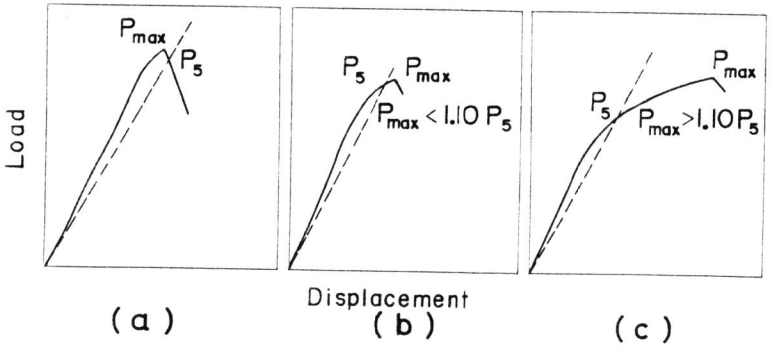

Figure 4 Three types of load-displacement record

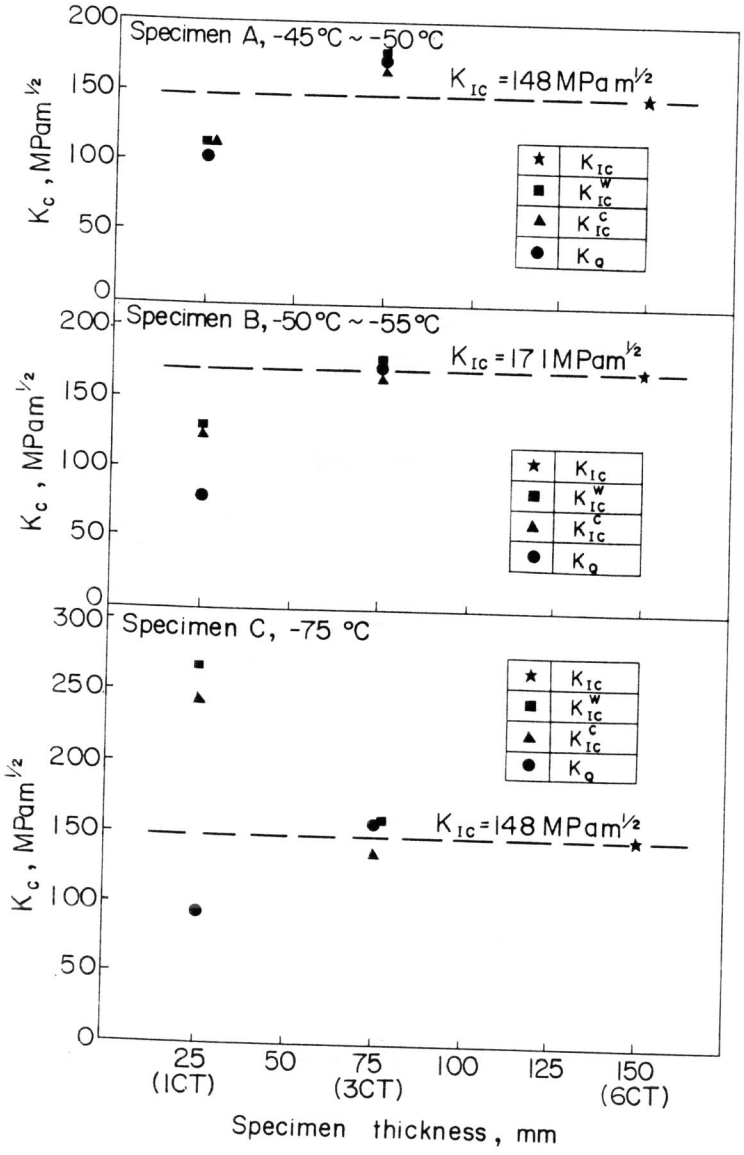

Figure 5 Effect of specimen size on fracture toughness value

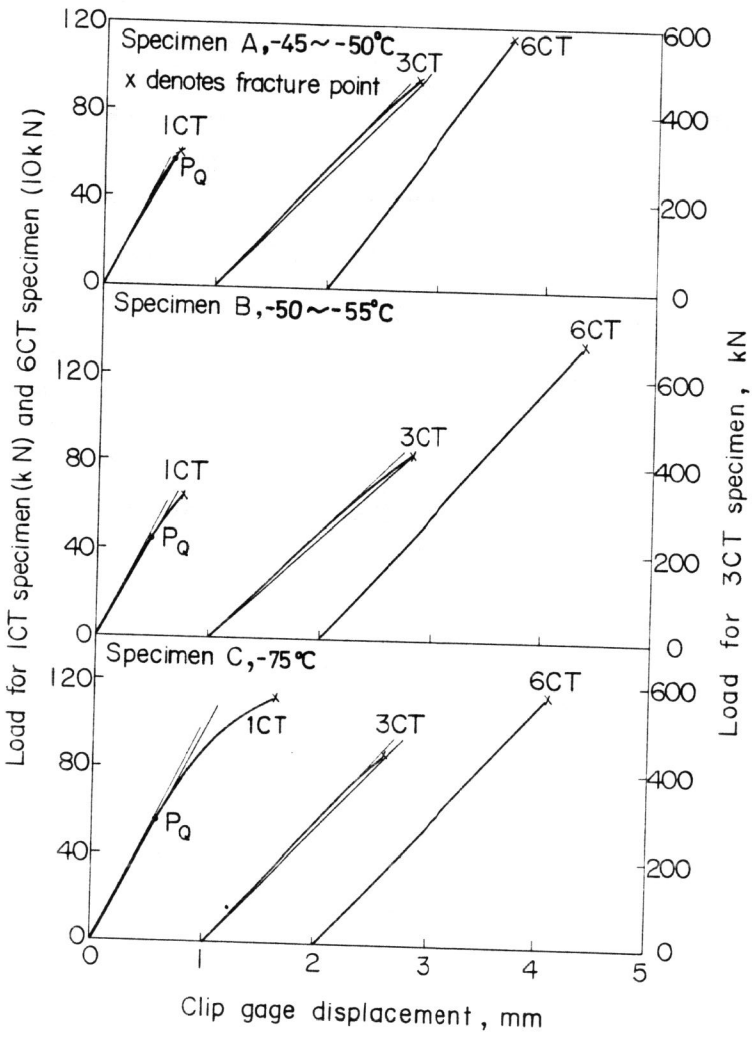

Figure 6 Load-displacement records of CT tests

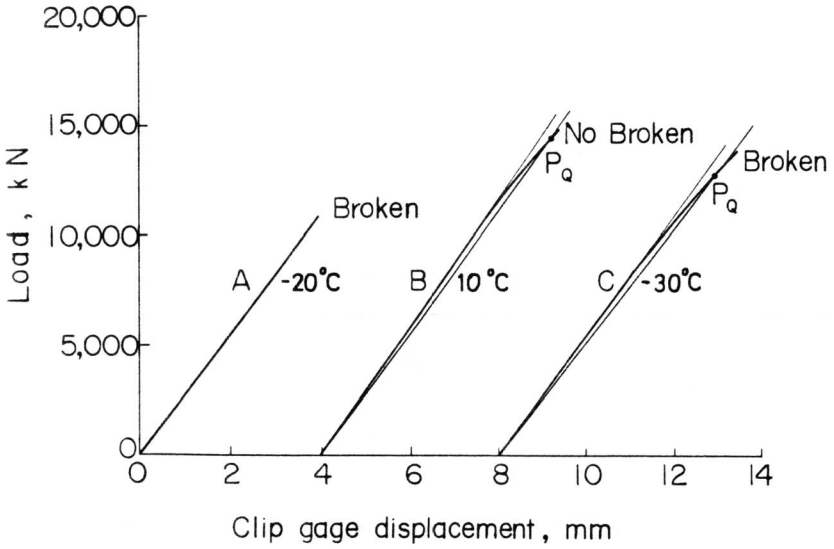

Figure 7 Load-displacement records of 14 RCT tests

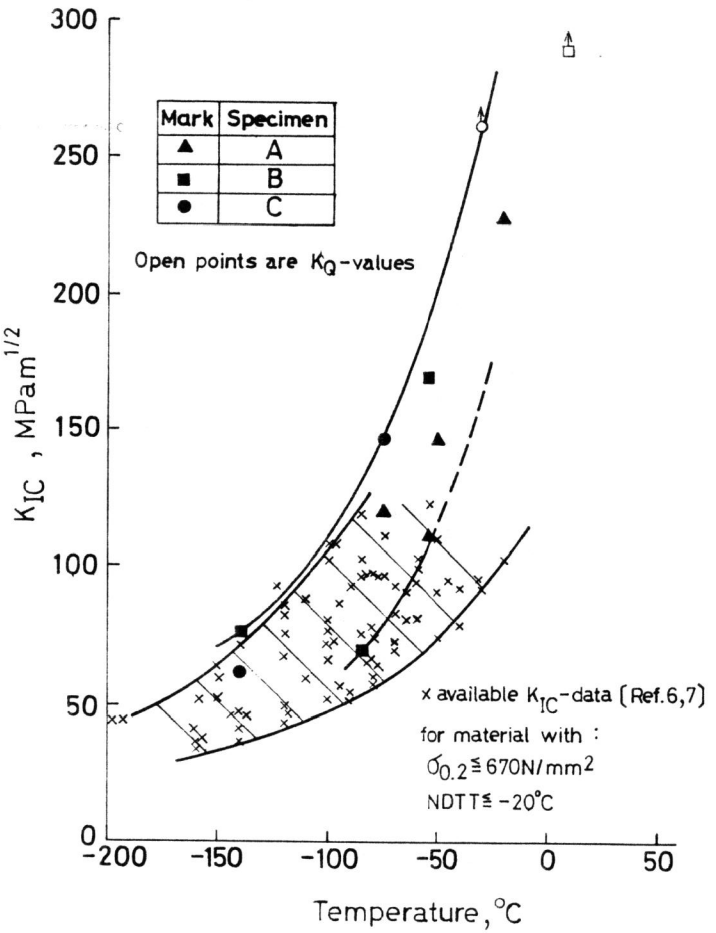

Figure 8 Fracture toughness K_{IC} of 2.8Ni-Cr-Mo-V steel for rotor forgings