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DEVELOPMENT OF A C-SHAPED FATIGUE SPECIMEN

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INTRODUCTION

Currently the most widely accepted technique to characterize fatigue and environment-assisted crack growth properties of metals involves the use of linear elastic fracture mechanics concept. Specifically, the rate of fatigue crack growth, da/dN, is expressed as a function of ΔK, the crack tip stress intensity factor range. The parameter ΔK is essentially a measure of the range of localized opening-mode crack tip stresses, and is independent of geometry. The compact tension specimens and bend specimens are commonly used for crack growth measurements. The measurement of crack growth rate requires that certain specimen dimensions exceed a critical size which is a function of K_{max} and the strength of the material. Because of this resistriction, it is often not possible to machine a standard test specimen from a given component configuration. This is particularly true for thick and thin walled pipes and forged cylinders. Underwood and Kendall [1] have developed a method for measuring plane-strain fracture toughness of materials from thick walled cylinders which utilizes a notched C-shaped test specimen, pin loaded in tension. This specimen has the advantage of most efficiently utilizing the available material to obtain the maximum possible triaxial constraint at the crack tip. It is logical to ask if a similar specimen can be used to investigate crack initiation and propagation in low and medium strength piping materials. The purpose of this paper is to describe this test specimen and to present the relationship between stress-intensity factor and applied load. This calibration was determined experimentally using a compliance technique. Fatigue crack growth rates were determined as a function of the range of stress intensity factor and the results were compared with those obtained using compact tension specimens.

TEST SPECIMEN

The fatigue specimens are shown in Figures 1 and 2. These are approximately one half of a disk cut from a forged cylinder with an internal radius r_1 = 4.63 cm and an outer radius r_2 = 9.63 cm. The surfaces are machined flat and drilled for pin loading in tension. Two loading positions are selected at X/W of 0.5 and 0.0 respectively where W is the specimen width and X is tne distance of the load line from the inner surface. The specimens are notched on the bore surface and fatigue precracked. The compliance of the specimens is measured using a clip gage located along the load line.

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The test specimens used for experimental K-calibration and fatigue crack growth rate measurements were machined from quenched and tempered AISI Type 403 stainless steel forgings. The material was quenched from 900°C and tempered at 620°C. Table 1 shows chemical composition and mechanical properties of this material.

EXPERIMENTAL PROCEDURE

The results of compliance tests for two specimen geometries, $X/W = 0.5$ and $X/W = 0.0$ are shown in Figures 1 and 2 respectively. Compliance, c, at a given crack length is given by

$$c = \frac{\delta B}{P} \tag{1}$$

where δ is load line displacement, B is specimen width and P is the applied load. The specimens were fatigue precracked using a sinusoidal load profile between two fixed load limits. The compliance was measured at an initial a/W. The crack was then extended by cyclic fatigue loading. The new crack length was measured and the compliance was also determined at the new a/W. This process was repeated until an a/W of approximately 0.75 was reached when the specimen failed in a brittle manner. A fifth order polynomial of form

$$c = A_1 + A_2 \left\{\frac{a}{W}\right\} + \ldots\ldots\ldots\ldots + A_n \left\{\frac{a}{W}\right\}^{n-1} \tag{2}$$

was fitted to the experimental compliance versus a/W curve. The stress intensity factor at a given crack length is given by

$$K = \frac{1}{B}\left\{\frac{E}{2W}\right\}^{1/2} P\left(\frac{dc}{d\left\{\frac{a}{W}\right\}}\right)^{1/2} \tag{3}$$

$dc/d\{a/W\}$ is determined from the fitted polynomial.

Fatigue crack growth was measured using a travelling microscope. Crack growth rates were based on the incremental change in crack length between readings.

RESULTS AND DISCUSSION

Figure 1 shows the compliance curve for the C-specimen with $X/W = 0.5$. Four specimens were used in these experiments and all experimental points are shown in this figure. Figure 2 shows the compliance curve for the C-specimen with $X/W = 0.0$. Figures 1 and 2 show that there are well defined compliance versus crack length relationships for these specimen geometries.

The K-calibration equations for the C-specimen are given by

$$K = \frac{P\sqrt{a}}{BW}\ Y \qquad \text{Pa}\cdot\text{m}^{1/2} \tag{4}$$

$$Y = \left[\frac{3.47941 \times 10^3}{a/W} - 3.59542 \times 10^4 + 1.37315 \times 10^5\left\{\frac{a}{W}\right\} - 2.28100 \times 10^5\left\{\frac{a}{W}\right\}^2 + 1.42485 \times 10^5\ (a/W)^3\right]^{0.5} \tag{5}$$

for $X/W = 0.5$, $r_2/r_1 = 2.1$

and

$$Y = \left[\frac{6.73031 \times 10^3}{a/W} - 5.76248 \times 10^4 + 1.82708 \times 10^5\left\{\frac{a}{W}\right\} - 2.54157 \times 10^5\left\{\frac{a}{W}\right\}^2 + 1.32145 \times 10^5\ (a/W)^3\right]^{0.5} \tag{6}$$

for $X/W = 0.0$, $r_2/r_1 = 2.1$

The experimental K-calibration curves are plotted in a parametric form against a/W in Figures 3 and 4. These figures also show the analytical K-calibration curves obtained by collocation method [1] and the agreement between the experimental and the analytical curves are excellent. A plane-strain formulation was applied on converting the compliance curves to stress-intensity factor. The true condition in the specimens was probably not plane-strain, particularly, at higher K. This may account for the differences between the experimental and the analytical K-calibration curves.

Fatigue crack growth rates for 3 C-specimens are plotted against the range of stress-intensity factor ΔK on a log-log plot, see Figure 5. The experiments were conducted at 8, 2 and 2×10^{-2} Hz and all experimental points lie in a narrow band showing that crack growth rates in this material are insensitive to frequency variations. Within the range of ΔK of 25 to 90 MPa·m$^{1/2}$, the crack growth rates can be expressed by the well known Paris' equation

$$\frac{da}{dN} = 10^{-12.0243} \qquad (\Delta K)^{3.334}\ \text{m/cycle} \tag{7}$$

where ΔK is in MPa·m$^{1/2}$.

Fatigue crack growth rates in the same material, measured by using compact tension specimens [2] are also shown in Figure 5 and the results from the C-specimens and compact tension specimens lie within a narrow experimental scatterband. The crack growth values measured in C-specimens are, therefore, true material properties and are independent of specimen geometry.

The maximum stress-intensity factor at failure for the C-specimens was approximately 100 MPa·m$^{1/2}$. This may be considered as an apparent plane strain fracture toughness K_Q, as the thickness criterion for measuring K_{Ic} was not satisfied. Consistent with the experimental observations of flat fracture surface and the absence of shear lips in the C-specimens the K_Q of 100 MPa·m$^{1/2}$ compares well with the true room temperature K_{Ic} of 87 MPa·m$^{1/2}$ [3].

CONCLUSIONS

The experimental compliance method can be used to determine K-calibration curves of non-standard specimens. The C-shaped specimens are suitable for determining fatigue properties of low and medium strength piping materials. The crack growth rates measured in these specimens as a function of stress-intensity range are true material properties and are independent of specimen geometry.

ACKNOWLEDGEMENTS

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REFERENCES

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3. HOSBONS, R. R., PACEY, A. J. and WOTTON, B. L., ASTM STP 570, 1975, 103.

Table 1 Chemical Composition and Mechanical Properties

CHEMICAL COMPOSITION OF AISI TYPE 403						
C	Mn	P	S	Si	Cr	Ni
0.125	0.54	0.023	0.009	0.26	11.98	0.25

MECHANICAL PROPERTIES OF AISI TYPE 403			
Yield Strength MPa	Tensile Strength MPa	Elongation %	Reduction of Area %
644.7	792.9	21	68.1

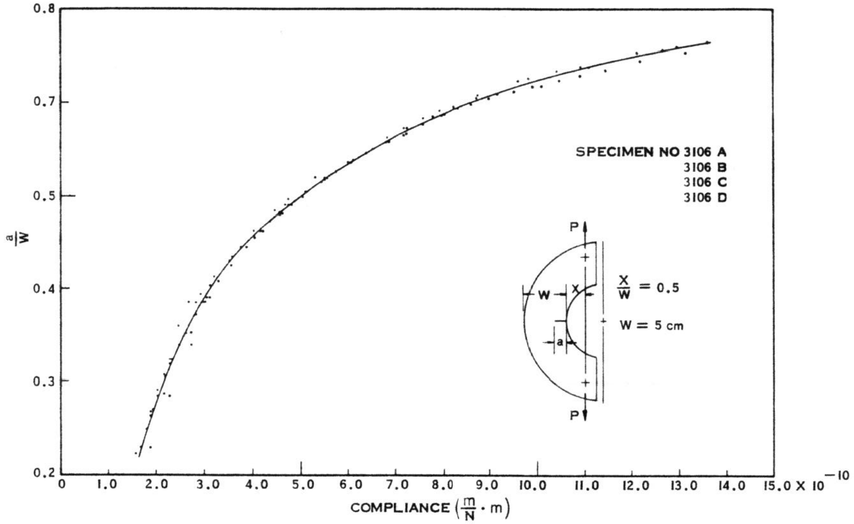

Figure 1 Compliance-test results

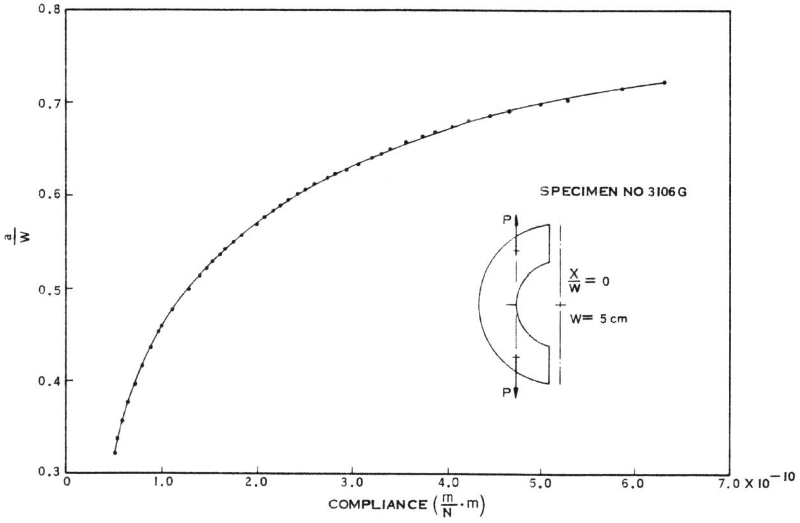

Figure 2 Compliance-test results

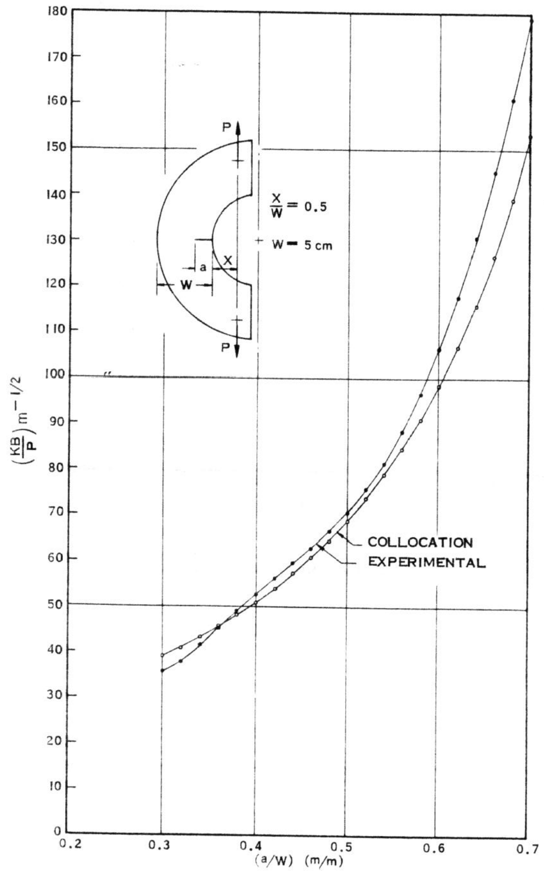

Figure 3 Stress-intensity factor calibration curves

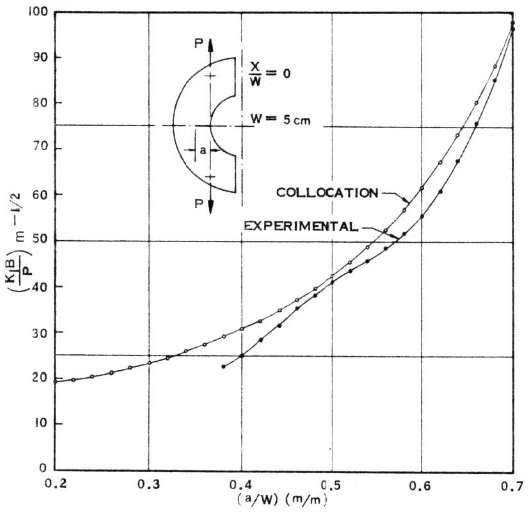

Figure 4 Stress-intensity factor calibration curves

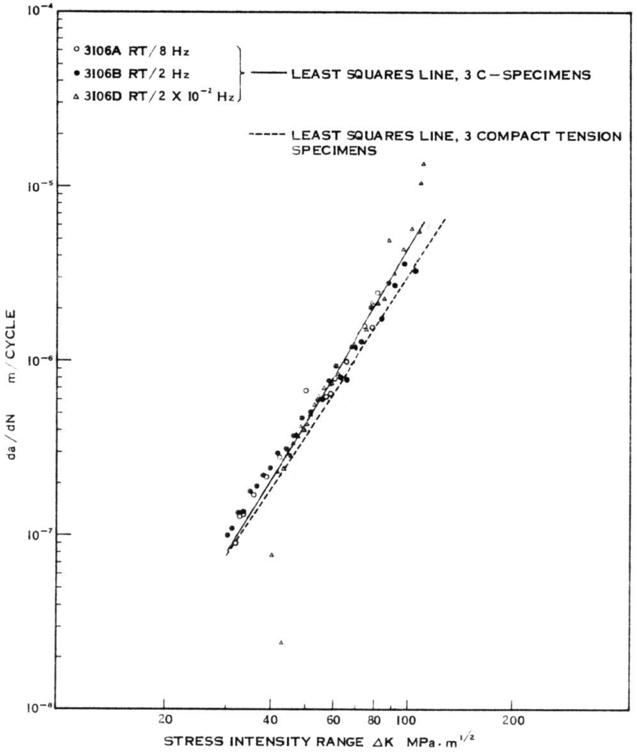

Figure 5 Fatigue crack growth rates for AISI Type 403 steel