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International Journal of Fatigue 28 (2006) 431–437
International Journal of Fatigue
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Fatigue crack growth for straight-fronted edge crack in a round bar

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Received 12 August 2004; received in revised form 12 May 2005; accepted 5 July 2005
Available online 29 September 2005

Abstract

In this paper, firstly fatigue crack growth for a straight-fronted edge crack in an elastic bar of circular cross-section is studied through experiments under pure fatigue axial loading. Three different initial notch depths are discussed. The relations between aspect ratio (b/c) and relative crack depth (b/D) are obtained, and it is shown that there is great difference in the growth of cracks with different front shapes and initial notch depths. Using the relations, predictions are made of the crack front shape and crack growth rate in the depth direction. Secondly, the variation of crack growth behavior is also studied under cyclic axial loading with steady torsion. Results show that Mode III loading superimposed on the cyclic Mode I leads to a significant reduction in the crack growth rates.
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Keywords: Surface crack; Aspect ratio; Steady torsion; Crack growth rate

1. Introduction

The fatigue growth analysis of surface cracks is one of the most important events for the safety operation of a structural component. The problem is complex and the closed solution is often not available because these flaws are three-dimensional in nature. The circular cylindrical metallic components (bars, wires, bolts, shafts, etc.) are commonly used in engineering structures and failure may occur under cyclic loading.

The fatigue failure of round bars often develops from surface defects, and thus many analyses have been carried out to determine the stress-intensity factors (SIF) along the front of an edge flaw [1–5]. An actual surface crack may usually be replaced by an equivalent circular arc or an elliptical-arc edge flaw. The stress-intensity factors have been published for part-circular, part-elliptical, or straight fronted cracks in a bar. The straight-fronted surface crack is often used in experiments due to easy of manufacturing, and this can be considered as an extreme shape of either the part-circle or part-ellipse surface cracks. The SIF's were obtained by using either numerical methods, such as finite element analysis, boundary integral equation and weight function methods, or experimental approaches. Newman and Raju [6] developed the SIF equation from a three-dimensional finite-element analysis of a semi-elliptical surface crack in an elastic finite thickness plate subjected to tension or bending. Forman and Shivakuma [7] assumed the actual cracks to be always part-circles that intersect the free surface of the bar at right angles. Through the studies on the bar and pipe, it was found that the shape of the crack front after some extensions of a straight-edge and a part-ellipse front are similar with that of a part-circle. Lin and Smith [8] adopted three-dimensional FEA techniques to simulate the development of a fatigue crack shape and showed that the aspect ratio is very sensitive to the initial crack geometry during its early growing stage, but tended towards a preferred front shape after some extension of the crack.

Tschegg [9] studied the fatigue crack growth under Mode III loading and showed that the fracture surface interaction between the fatigue crack surfaces induced 'crack closure' at the crack tip and a significant reduction of crack growth rates was achieved. Fonte and Freitas [10] analyzed the influence of steady torsion loading on fatigue crack growth rates under rotating or reverse bending. Similar results are obtained showing that the steady Mode III loading superimposed on the cyclic Mode I leads to a significant reduction of the crack growth rate.

In this paper, experimental results of fatigue crack growth for a straight-fronted edge crack in an elastic bar under axial loading with or without steady torsion are given. Three different initial notch depths are discussed. The relations of aspect ratio and relative crack depth are obtained and it is

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doi:10.1016/j.ijfatigue.2005.07.036

Table 1
Chemical composition of steel S45

Element	C	Mn	Ni	Cr	Mo	Si	P	S	Gu
wt%	0.4556	0.6490	0.0458	0.0735	0.0111	0.2310	0.0108	0.0132	0.1398

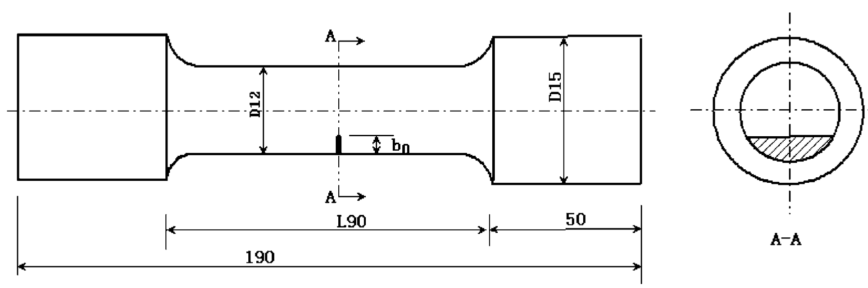

Fig. 1. Details of the specimen geometry.

shown that the growth of the crack fronts is dependent on the initial notch depth. Using the relations, the crack front shape and crack growth rate in the depth direction can be predicted. Under cyclic tension with steady torsion, the crack growth is retarded. This is related to the increase of plastic zone size near the crack front and to some extent may be related to the 'crack closure effect'.

2. Test material and specimens

The test material was carbon steel S45. Its composition is given in Table 1. The heat treatment consisted of austenizing at 1123 K for 1.5 h, oil quenching and tempering at 903 K for 1 h. The mechanical properties attained by this heat treatment are summarized as follows: monotonic tensile yield strength $\sigma_0=$ 635.07 MPa, nominal ultimate tensile strength $\sigma_m=$ 775.65 MPa, true ultimate tensile strength $\sigma_f=2101.65$ MPa, reduction of area $\phi=62.87\%$, Young's modulus $E=206$ GPa, true fracture logarithmic strain $\varepsilon_f=0.991$.

The outer geometry configuration of a specimen is shown as Fig. 1. The diameter D is 12 mm and the length L is 90 mm in the test section. Using linear cutting machine surface edge cracks were cut with three different initial flaw depths b_0: 1.0, 2.0, and 3.0 mm. The geometric parameters of the test section of a specimen and of the crack growing process are shown in Figs. 2 and 3. An equivalent elliptical-arc edge flaw is used to replace the actual part-through crack after some extension. In Fig. 2, $b_1=OB_1$ is the current crack depth at time t_1. The crack front may be approximated by an elliptical curve with major axis $2a$ and minor axis $2b$. Note that, the length of the major axis of the assumed ellipse $2a$ is only an estimated value. In the actual experiment, the location of the external surface crack front is measured by h, the distance from the intersected point A to the central axis of symmetry OY and y, the distance from point A to the horizontal axis OX. The crack length in the surface direction can be obtained by way of calculating the chord shown in Fig. 3. The front of the initial straight surface crack is denoted by B_0A_0, and the initial chord from A_0 to o is $c_0=OA_0$. When the crack is developed, the intersection moves to A_1 and the current chord is $c_1=OA_1$, which can be calculated by the location of the point A_i and the formula $c_1=\sqrt{h_1^2+y_1^2}$. D and R are the diameter and radius of the specimen, respectively.

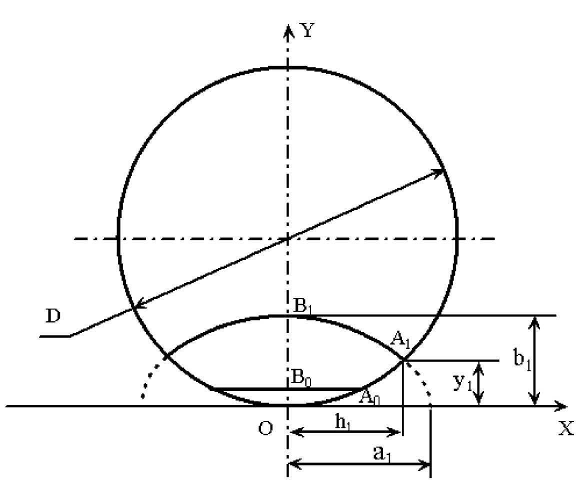

Fig. 2. Surface crack geometric parameters.

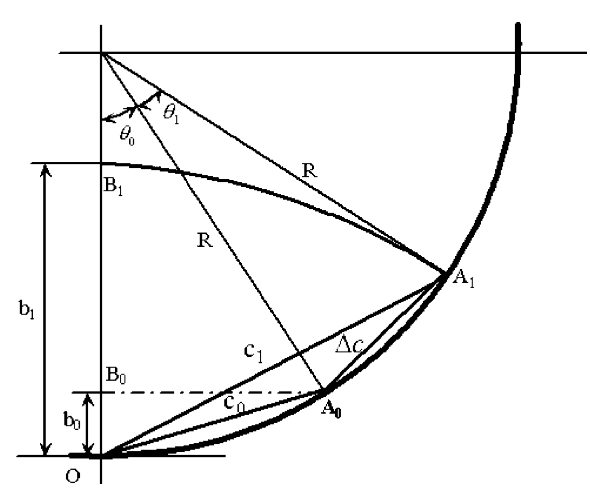

Fig. 3. Crack growth rule in the surface direction.

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