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Fatigue crack growth rate in miniature specimens using resonance

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ABSTRACT

The method of crack growth rate measurement in miniature single edge notched (SEN) cantilever specimen at stress ratio $R \sim -1$ is presented. The resonance circuit is formed by the cantilever specimen with inertial yoke at its free end excited by alternating electromagnetic field. The parameters of the harmonic excitation are controlled by the phase shift technique. The crack length is estimated from specimen compliance added by the crack opening. The stress intensity factor is computed from the applied bending moment. Linear elastic fracture mechanics with standard shape functions corresponding to the particular specimen geometry and applied loading are used. The analysis of signal from single piezoelectric accelerometer provides data for the estimation of crack length and applied stress intensity factor, making the method very simple and inexpensive, yet reasonably accurate.

The crack length measurement was calibrated using fractographic marking technique. The presented method was validated by performing crack growth rate tests in miniature $4 \times 3 \times 32$ mm beam specimens with 150° chevron notch. 7075 aluminium alloy and 4043 high strength steel were tested at load frequency of 110 and 160 Hz respectively. The crack growth curves were measured in both load increase and load reduction mode and the resulting crack compare well with the baseline data available for standard central crack (CCT) specimens.

1. Introduction

Small specimen test technology has become an integral part of several areas of material science where the tested material availability is limited. For example, irradiated material quantities are very low, regardless whether they originate from surveillance programs, or are subjected to controlled irradiation at the beamlines. Emerging manufacturing technologies such as spark plasma sintering, hot isostatic pressing, near net shape forming by plasma spray and other technologies are also limited in material volume. In all of the above cases, the testing of material properties calls for the use of miniature specimens.

The fatigue crack growth rate (FCGR) as a function of applied load is a crucial engineering property defining the service lives of aircraft, power plants, and other machines and structures, where the fatigue crack growth is expected under the defect tolerant approach. There exists a plethora of methods for FCGR testing of small specimens including three point bending of thin $0.8 \times 2 \times 7.9$ mm beam specimens [1], tensile loading of circular rods as small as 26×8 mm [2], or testing of double cantilever beams of $19 \times 6.4 \times 3.2$ mm size [3]. In these tests, different methods of loading and crack length measurements are used. Electromagnetic testing machines [3], dynamic mechanical analyzers [4] or piezoelectric actuators [5] usually offer sufficient force to test at least in the near threshold regime, i.e. for low ΔK. Standard servohydraulic test machines are also convenient for the task [6] despite the limitation to lower loading frequencies. The crack growth in small specimens is usually monitored using a travelling light microscope [4,6,7] or replica technique [8] providing surface crack length. Additional information describing the average crack length is necessary due to the curved nature of the crack fronts. The average or integral crack length may be obtained by compliance methods [9], or potential drop method [10]. However, the use of these methods for small specimen testing is very scarce, due to the experimental difficulties encountered with small specimens. The tedious procedure of optical crack length measurement combined with specimen manufacturing difficulties due to tight dimensional tolerance make the crack growth experiment on a small specimen a challenging task. Therefore, a new method was developed with the aim to find a fast and experimentally easy method, using simple specimen geometry that is robust to specimen dimensional inaccuracies. The new method was designed to follow as much of the ASTM standard E647 [11] as possible in order to obtain results comparable with other techniques. At the same time utilizing the resonance bending test approach [12] appeared

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to be very convenient. This method excites the specimen at its exact resonance at stress ratio $R \cong -1$. One would be tempted to use the resonance frequency changes for crack growth measurement [13,14]. Unfortunately, the material property changes taking place during cycling loading also influence the resonance frequency [15] and it is necessary to separate these two effects for accurate crack measurement. For this separation and detection of crack initiation phase, measurement of specimen damping is a promising approach. Damping can be characterized directly from vibration decay curves (see i.e. [12,16]). This technique requires stopping the fatigue experiment or even removing the sample from loading fixture [16]. The measurements based on vibration frequency spectrum (see i.e. [17,18]) do not require experiment stopping. For all of these damping based methods, the calibration of crack length is a rather complex task depending on material, geometry and loading.

The symmetrical bending load used at resonance fatigue tests enables to cancel material property changes without test procedure modification, using a differential approach. At $R = -1$, the loading cycle can be separated in closed crack and open crack segments. The compliance difference of these segments is directly related to fatigue crack growth of a fatigue crack and effectively eliminates most of the other effects. The differential compliance method was first introduced in [19] where compliance difference of specimen with closed and open crack was related to crack length. Compliance difference was evaluated from loading force asymmetry of displacement controlled cycle in [19]. We present a different approach to obtain crack added compliance from time domain data fitting together with analytic formulas to transform this compliance to crack length. This new method for crack length measurement is described in the following paragraphs together with its application to test 4340 steel and 7075 aluminium alloy specimens.

2. Materials and methods

2.1. Fatigue test specimens

Aluminium alloy 7075-T651 (Otto Fuchs KG, Meinerzhagen, Germany) and 4340 high strength steel were selected for validation of the proposed test. Small cantilevers of dimensions 4 mm $*$ 3 mm $*$ 32 mm (h, b, l) were cut by diamond blade. The 7075-T651 specimens were cut from extruded bars of 90 mm diameter approximately in L-R orientation. The 4340 specimens were cut from large thick walled tube in L-C direction. Chevron notch of $\alpha = 150^\circ$ at the mid-length according to Fig. 1 was cut in a special fixture using a 0.35 mm thick diamond blade. Finally, the tip of the chevron was sharpened using an oscillating razor blade. ASTM E475 recommends specimen size based on minimum uncracked ligament length *h-a* and Irwin's plastic zone size. The maximum applied stress intensity factor K_{max} then relates to material yield strength σ_y and crack length as $(h - a) = (4/\pi)(K_{max}/\sigma_y)^2$. This requirement is easily followed by limiting the maximum values of stress intensity factor K_{max} or crack length a even for the presented specimen geometry. For a = 2 mm the stress intensity factor upper limits for 7075 and 4340 are about 20 $\mathrm{MPa}\sqrt{\mathrm{m}}$ and 30 $\mathrm{MPa}\sqrt{\mathrm{m}}$ respectively. The thickness of the specimen b is recommended to be $b \leqslant h/2$ in order to enable crack curvature correction. The thickness requirement was violated in order to avoid torsional vibration of the specimen, however as shown later the crack curvature was still acceptable.

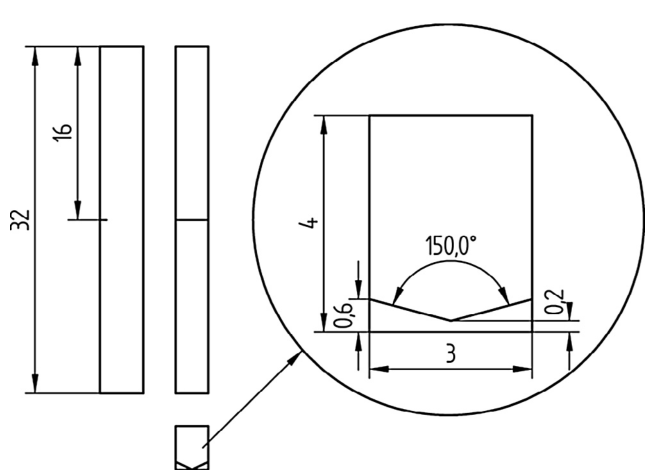

Fig. 1. Test specimen geometry.

2.2. Cantilever bending test

One end of the cantilever specimen is clamped in a special jig mounted to a heavy base, the free end is equipped by a ferromagnetic yoke in a T-configuration according to Fig. 2. The movement of the yoke is measured by a piezoelectric accelerometer of type KS94B (MMF, Radebeul, Germany) and sampled by LabJack data acquisition module (LabJack Corporation, Lakewood, CO, USA). The excitation system is described in detail in [12], therefore only brief description is given. The specimen-yoke vibration system is excited by alternating harmonic signal distributed to two electromagnets. The excitation coil current is measured and its phase is kept at phase shift $\varphi = \frac{\pi}{2}$ by the PID loop. Therefore the specimen-yoke assembly is excited at its resonance frequency. The maximum stress intensity factor K_{max} achieved during the loading cycle is controlled by the amplitude of the excitation current by another independent PID loop. During the test, specimen bending moment M_t, crack length a and maximum value of stress intensity factor K_{max} are evaluated from accelerometer signal and recorded together with the number of cycles N. The raw accelerometer data are also saved for future processing. The formulas used for evaluation of accelerometer signal are presented below.

2.2.1. Modelling of applied bending moment

A simple and approximate model to characterize the bending moment, M_t, applied to the uncracked specimen is presented. The uncracked specimen-yoke system in Fig. 2 can be modelled by a Timoshenko cantilever beam with a rigid body attached to its free end. The following assumptions are taken:

- the specimens behaves as a massless Timoshenko beam (yoke to specimen mass ratio is around 300:1)
- the free undamped vibration is considered (damping ratio is very low and is automatically compensated by excitation)
- the clamping is ideal
- the yoke does not deform

The model uses nomenclature in Figs. 2 and 3. The boundary condition describing yoke reactions is applied at point P as:

$$\begin{bmatrix} M \\ F \end{bmatrix} = \begin{bmatrix} J\ddot{\alpha} \\ m(d\ddot{\alpha} + \ddot{u}) \end{bmatrix} \tag{1}$$

Here α is the angle of yoke rotation, u is the deflection of the point P, dots denote time derivative. The yoke is characterized by its mass m, the distance d of its center of gravity T to boundary condition point P and by its moment of inertia J with respect to the axis of in plane rotation passing through point P. Under these assumptions, the corresponding set of ordinal differential equations for the rota-