A COMPARISON OF TWO EXPERIMENTAL METHODS FOR ASSESSING THE INFLUENCE OF INITIAL DEFECTS ON FATIGUE LIFE

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ABSTRACT

Rotating bending tests have been, up to now, typically used for the determination of S/N curves. In this paper, a method is proposed that allows the determination of the fatigue limit curve and the crack growth curve by means of such rotating bending tests. For this purpose, flaws of controlled shape and size are introduced on the surface of conventional round bar specimens. The rotating bending test rig is equipped with additional hardware for optical crack length measurement. The stress at incipient crack growth gives a point in the fatigue limit (Kitagawa-Takahashi) diagram. After the crack starts to grow, photomicrographs are taken in regular intervals in order to obtain the crack growth curve. – The fatigue limit and crack growth curves obtained from the rotating bending tests are compared with results from conventional single edge notch bending specimens. Agreement is good, with the results from the rotating bending experiments lying somewhat on the conservative side. Some factors which may contribute to these differences are the different type of loading and the simplified calculation of the stress intensity factor in the rotating bending tests.

1 INTRODUCTION

Most machine parts contain initial flaws caused by the manufacturing process (typical examples are imperfections from casting or forging). In mechanical engineering, it has been standard practice to assume a "perfect" material and to assess its fatigue life by means of S/N curves. Alternatively, S/N curves for specimens with artificially introduced flaws may be measured, a common way for assessing the sensitivity of turbomachinery components to foreign-object damage. Such S/N curves are valid only for machine parts with similar flaws, which limits the attractivity of this concept despite its simplicity.

Rather than using such a simplified assessment of the sensitivity to initial flaws, a defect can also be regarded as a (possibly irregularly shaped) crack which starts to grow if the amplitude of the applied stress intensity factor exceeds its threshold value, thus leading to failure after a finite number of load cycles. There exist two means for characterizing the fatigue behavior of such a flaw: first, the curve of defect size (i.e., crack length) vs. the stress amplitude at which the flaw starts to grow; this fatigue limit curve represents the dependence of the high-cycle fatigue limit on the size of the initial flaw, and is also known as the Kitagawa-Takahashi [1] diagram. On the other hand, once the flaw has started to grow, its growth rate is also governed by the applied stress intensity amplitude; the transition and low cycle fatigue regime of an S/N curve is thus described, in terms of fracture mechanics, by the diagram of crack growth rate vs. stress intensity amplitude.

Both diagrams are traditionally determined experimentally by compact tension, center cracked tension, or single-edge notch bending specimens. An alternative, very efficient test method that has been successfully employed for determining S/N curves is the four-point rotating bending test using round bar specimens.

In this paper, a method is proposed that allows the determination of the fatigue limit curve and the crack growth curve by means of such rotating bending tests.

2 SPECIMEN PREPARATION

Conventional round bar specimens are manufactured from a single batch of a typical heat-treatable steel (34CrNiMo4). Subsequently, flaws of controlled shape and size are introduced on the surface of the specimen. Due to the constant bending moment in the four-point bending test, the results are not sensitive to the exact position of the defects. Experience has shown that drilled holes with a depth equal to the diameter are best suited for this purpose. In the present investigations, specimens of 7.5 mm minimum diameter with drilled holes of 0.25 and 0.30 mm diameter as well as milled holes of 0.60 mm diameter are used (Fig. 1). As the flaws are much smaller than the specimen, the geometry correction factor may be set to unity, and the stress intensity amplitude ΔK is determined from the applied stress amplitude $\Delta\sigma$ and the hole radius a as $\Delta K = \Delta\sigma\sqrt{\pi a}$.

Alternatively, a fatigue crack of well-defined length could be introduced by controlled cycling between two adjacent drilled holes (Fig. 2). However, it proved difficult to generate such a flaw; the experiments were therefore conducted using single holes.

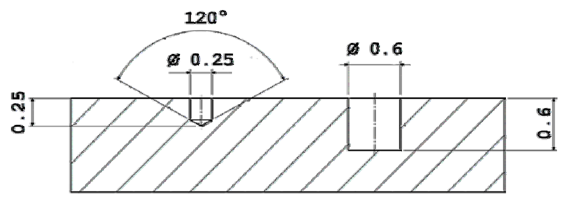

Figure 1: Imperfections used: drilled hole (left), milled hole (right)

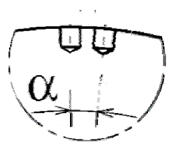

Figure 2: Double drilled hole

3 EXPERIMENTAL SETUP

Fig. 3 shows the experimental setup. The rotating bending test rig is equipped with additional hardware for optical crack measurement, i.e., a CCD camera and a PC with a frame grabber card so that the image may be stored immediately on a hard disk. The post-processing is done subsequently off-line. The camera is triggered by a shaft encoder coupled to the rotating bending test rig so that each image of the flaw is taken at the same angular position of the specimen. Lighting is provided by a stroboscope triggered simultaneously with the camera.

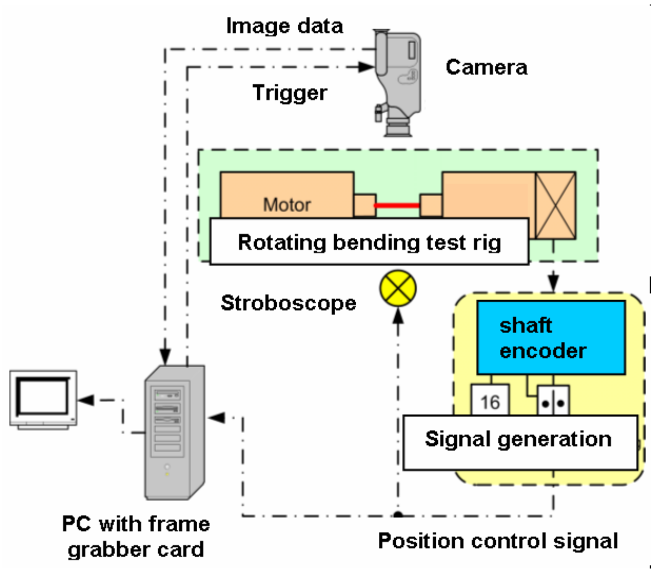

Figure 3: Experimental setup

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4 FATIGUE LIMIT CURVE

Fig. 4 displays the high-cycle fatigue limit curve (Kitagawa-Takahashi diagram). The stress amplitude $\Delta\sigma$ is plotted on the ordinate; it is calculated from the stress intensity factor at incipient crack growth (the threshold stress intensity factor) ΔK_{th} and the flaw size a via $\Delta\sigma = \Delta K_{th} / \sqrt{\pi a}$. For sufficiently large flaws, the threshold stress intensity factor ΔK_{th} is constant, which gives a straight line with a slope of -1/2 on a log-log scale; this is the right branch of the fatigue limit curve in Fig. 4.

As the flaw size becomes smaller than a certain material specific length, at least when approaching the microstructural length scale of the material, the fatigue limit does not depend anymore on the defect size only [1]. In our simplified plot, this is depicted by the horizontal branch in the Kitagawa-Takahashi diagram. Its stress amplitude corresponds to the high cycle fatigue limit of the defect-free specimens.

The rotating bending tests give an average threshold value of $\Delta K_{\mathrm{th}}\approx 10.6$ MPa√m. From single edge bending tests conducted for comparison, $\Delta K_{\mathrm{th}}\approx 13.4$ MPa√m is obtained. Although the results from the rotating bending tests are somewhat conservative, this seems appropriate for purposes of engineering design.

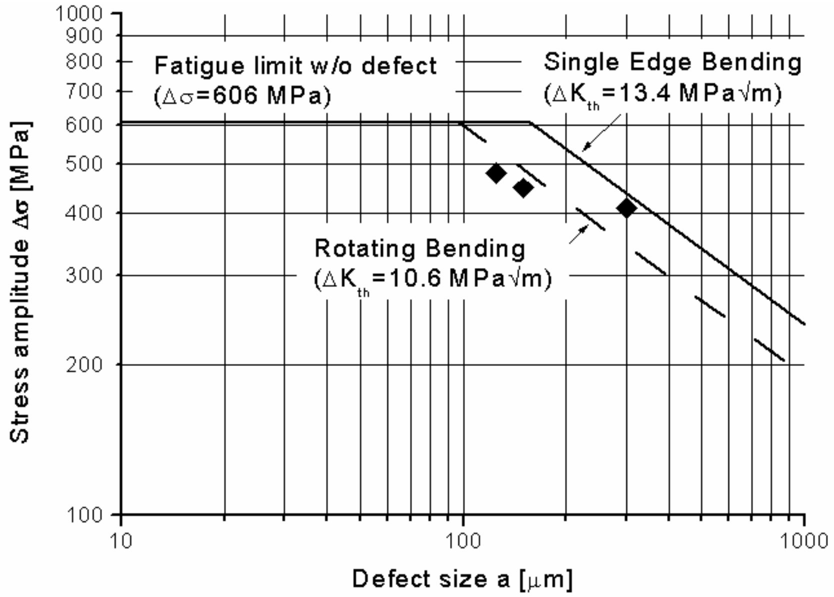

Figure 4: Fatigue limit diagram: comparison of rotating bending tests (data points and dashed mean curve) and single edge notch beam bending tests (full line)

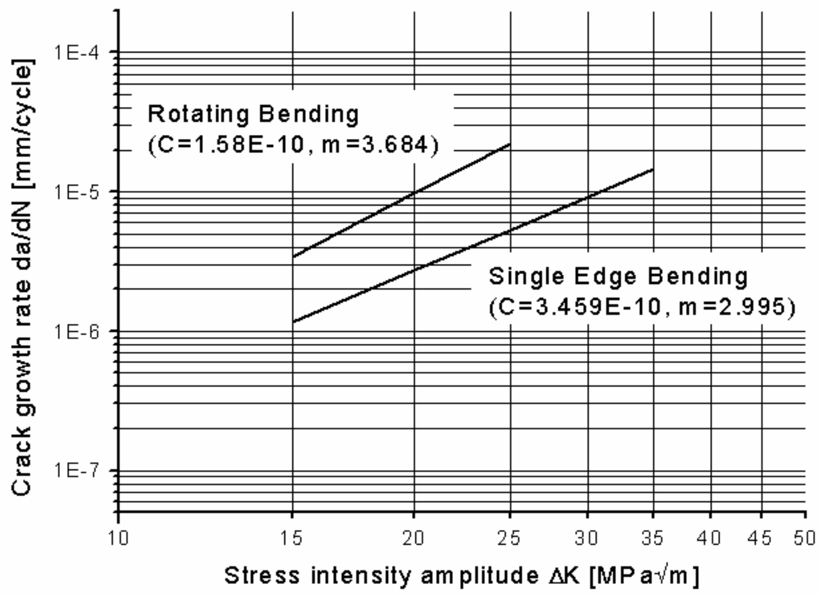

Figure 5: Comparison of the crack growth behavior in rotating bending tests and single edge notch beam bending tests

Finally, it should be noted that the corner-shaped transition between the two branches is clearly an idealization due to the lack of more extensive experimental data: in reality, the curve exhibits a smooth transition, as may be seen from the data points of the rotating bending tests in Fig. 4.

5 CRACK GROWTH CURVE

After a crack starts to grow, photomicrographs are taken in regular intervals. The crack length is measured manually from the photomicrographs; for future investigations it is planned to replace this manual post-processing by digital image processing. The middle regime of the crack growth curve can be approximated by the Paris equation $da/dN = C \cdot \Delta K^m$, giving a straight line in a log-log diagram of crack growth rate *da/dN* vs. stress intensity amplitude ΔK.

In Fig. 5, the averaged Paris curve from rotating bending tests on three specimens is compared to a curve obtained from single edge bending tests. As for the Kitagawa-Takahashi diagram, the results from the rotating bending experiments are on the conservative side.

6 CONCLUSION

Four-point rotating bending experiments appear as a simple and reliable alternative to standard fatigue test methods. The results are somewhat conservative compared to the standard tests on single edge notched bending specimens, but seem appropriate for purposes of mechanical design. The conservative results might be contributed on the one hand to the simplified ΔK calculation without taking into account the real shape of the crack, on the other hand to the different type of loading and to the short crack effect; further investigations are underway.

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