DETERMINATION OF SHORT CRACK DEPTH WITH AN ACOUSTIC MICROSCOPE

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INTRODUCTION

For the prediction of the lifetime of any component, subjected to alternating stresses, the knowledge of the growth behavior of defects is essential. Most methods of monitoring the propagation of short cracks are confined to measuring the length of the crack on the surface [1]. The depth of the crack must be determined indirectly, assuming the shape of the crack. Acoustic waves, on the other hand, offer the possibility of measuring the depth directly, since acoustic waves can penetrate into the material. This allows the measurement not only of the growth behavior of fatigue cracks on the surface, but also changes of the crack geometry inside the specimen. Current applications of direct acoustic monitoring of crack growth have been developed for cracks of the order of millimeters. One acoustic depth measurement technique is the Time-of-Flight-Diffraction (TOFD) technique [2-4], which is based on timing measurements of the scattered signals from the defect. Our investigations are concerned with the application of TOFD technique for the depth measurement of short cracks (70-200 μm in surface length) using a scanning acoustic microscope (SAM) [5-6]. Depth measurements were first carried out on cracks in the transparent material polystyrene. This allows a direct comparison between acoustic and optical depth measurements. Subsequently, the depth of fatigue cracks in an Al alloy were measured, and the acoustic measurements were compared with direct measurements of the crack geometry by sectioning the crack.

MEASUREMENT TECHNIQUE

Conventional TOFD technique uses a transmitter and a separate receiver to fire acoustic pulses into the material and to detect the signals diffracted from the crack, respectively. In an acoustic microscope the point focus lens acts as both the transmitter and the receiver. In order to determine the depth of a crack, the SAM can be operated in a tone burst/CW mode to locate the crack on the surface and also in an impulse excitation mode, used for TOFD. Once the crack is located, the lens is moved in equally spaced steps across the specimen surface perpendicular to the trace of the crack, operating the SAM in the impulse excitation mode. After the scan is completed, the sampled and stored signals are converted into grey scales and displaced on a frame store. This display is referred to below as an s(t,y)-image (scanning, time, y position). Each s(t,y)-image consists of 512x512 image points with the horizontal axis representing time and the vertical axis representing the position of the lens. Fig. 1a shows the various signals,
which can occur from a surface-breaking crack, and Fig. 1b shows a schematic s(t,y)-image. The signals are [7]:

a) specular reflection,
b) surface wave transmission,
c) surface wave reflection,
d) mouth diffracted signal,
e) crack face reflection signal,
f) tip diffracted signal.

Of particular interest are the signals e) and f), because they depend on the crack geometry and can be used to determine the inclination angle $\beta$ and the depth, $d$, of the crack. From the time interval, $T$, (see Fig. 1b) between the specular reflection and the vertex of the hyperbola shaped signal f) and the elastic wave speed $c$, the crack depth can be calculated as $d=1/2(cT)$. The shift, $Y$, between the vertex of the tip diffracted signal and the crossing point of the surface wave reflection can be used to determine the inclination angle $\beta$ of the crack: $\beta=\arctan(d/Y)$. The slope, $m=dy/dt$, of the crack face reflection signal depends also on the inclination angle $\beta$ and can therefore be exploited to calculate $\beta=\arcsin(1/2ctm)$.

The signals a)-f) are very different in amplitude. There is the strong specular reflection due to the impedance mismatch between the coupling fluid and the specimen, and the very small tip diffracted signal, resulting in part because the diffracted energy is spread over a large range of angles. To enhance the contrast of the tip diffracted signal and to improve the signal-to-noise ratio image processing and signal averaging is necessary. Thus the following experimental results show processed s(t,y)-images after removing the crack independent specular and surface wave transmission signal.

![Fig. 1. a) Ray diagrams of reflected and diffracted signals from a specimen containing an oblique surface-breaking crack. b) Schematic s(t,y)-image with signals indicated in a). The depth of the crack can be calculated from the time interval T, and the wave speed c as $d=1/2(cT)$.](image-url)
RESULTS

Polystyrene is a transparent, brittle polymer with acoustic wave velocities [8]:
longitudinal $c_L = 2.35 \, \mu m/\mu s$, shear $c_S = 1.12 \, \mu m/\mu s$ and Rayleigh $c_R = 1.048 \, \mu m/\mu s$. Cracks in polystyrene were produced in a 0.7 mm thick slice and depth measurements were carried out near the end of a long, through-thickness wedge-shaped crack. Fig. 2a shows an $s(t,y)$-image taken near the end of this long crack. The two diffracted signals appearing on the right side of the $s(t,y)$-image are caused by a kinked crack. The first diffracted signal is from the 53 $\mu m$ deep kink and the second is caused by the 76 $\mu m$ deep crack tip. Furthermore, a shift of 9 $\mu m$ between the two vertices of the hyperbola-shaped diffracted signals could be measured. Taking this shift, the inclination angle $\beta$ (for definition of $\beta$ see Fig. 1a) of the kink could be calculated as 69°. This inclined segment of the crack should give rise to a face reflection signal, such as line e) in Fig. 1b, but no such line appears in the $s(t,y)$-image. However, optical measurements showed that the inclined segment is actually curved in shape rather than straight, and this could account for the lack of the crack face reflection. Fig. 2b shows a schematic cross-section through the crack and Table 1 gives a comparison between the acoustic and the optical measurements. The difference between the two is less than 5%. On the left side of the $s(t,y)$-image the hyperbola shaped mouth diffraction signal (line d in Fig. 1b) can be seen. Furthermore, two surface wave reflections appear, because surface waves can be generated and reflected on both sides of the crack. This results in a crossing pattern in the $s(t,y)$-image [5]. In addition to the signals a)-f) (Fig. 1b) two lines, labelled a and b, appear in Fig. 2a. They are surface waves scattered at the crack mouth back to the lens. An overlap between the $s(t,y)$-image of Fig. 2a and the signal time-of-flight traces calculated by ray theory is given in Fig. 2c. The ray theory calculations are based on calculating the travel time for pulses propagating along the appropriate ray path using the crack geometry in Fig. 2b.

An acoustic image of a fatigue crack in Al-Li alloy 8090 is shown in Fig. 3a. The image is taken at a frequency of 350 MHz and zero defocus, operating the SAM in the single frequency/CW mode (defocus is the distance the lens is moved towards the specimen relative to focusing on the surface). Fig. 3b shows the processed $s(t,y)$-image taken along the indicated scanning line of Fig. 3a. However, whereas the acoustic waves in water couple strongly only to longitudinal waves in polystyrene, in aluminum both longitudinal and shear waves are exited. Thus three tip diffracted signal can appear: the longitudinal, the shear and a mode converted. This, together with the more complex geometry of cracks in metals, complicates the evaluation of the $s(t,y)$-image. In Fig. 3b the shear wave signal from the tip appears last (farthest from the surface wave reflection crossing point); its vertex is marked in Fig. 3b. The crack depth obtained from the measured time distance $T$ (see Fig. 1b) and the shear wave velocity is 42 $\mu m$. Furthermore, the vertex of this tip diffracted signal is shifted by 7 $\mu m$ in the $y$ direction, which means that the tip of the crack is displaced by 7 $\mu m$ from directly below the mouth of the crack.

In order to confirm our acoustic measurements, a cross-section through the crack was carried out. Fig. 3c shows an acoustic micrograph of the cross-section taken at 550 MHz and zero defocus. The depth of the crack obtained from this image is 43 $\mu m$ and a shift between crack tip (indicated by the arrow in Fig. 3c) and the mouth of 6.5 $\mu m$. The kink visible in Fig. 3c is 8 $\mu m$ deep and could not be determined from the $s(t,y)$-image, because the kink is not deep enough and thus any signal from it is obscured by the strong and broad specular and surface signals. Fig. 3d shows an overlap between the $s(t,y)$-image of Fig. 3b and the time-of-flight traces calculated by ray theory, based on the crack geometry in Fig. 3d. The three approximately hyperbola-shaped white lines are the traces for tip diffracted longitudinal (first), mode converted (middle) and shear waves (last). The mode converted signal is due to energy transfer between the longitudinal and the shear wave at scattering sites and vice versa. The vertical black lines are the specular (left) and the surface wave transmission signal (right), respectively. The crossing pattern is the trace of the two surface wave reflection signals. The agreement between the ray traces and the experimental signals is fair and any remaining discrepancy could be due to errors in wave speeds and the scanning position and the position of the cross-section might be slightly different.
Fig. 2. a) An s(t,y)-image from a kinked crack in polystyrene after image processing. b) Schematic crack geometry of the crack measured in a). c) Overlap between a) and ray theory calculations.

Table 1. Comparison between direct optical and acoustic depth measurements.

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<th>µm</th>
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DISCUSSION

The present results demonstrate the capability of the time-of-flight diffraction technique in an acoustic microscopy to determine the depth of short cracks, not only in the model material polystyrene, but also in Al-Li alloy 8090. Unlike the straight cracks in polystyrene, cracks in metals can grow with a more irregular shape, i.e. the cracks are kinked and the tip may be irregular. From all the kinks diffracted signals can occur, which complicate the recognition of the tip diffracted signal. Furthermore, in metals the SAM couples to both shear and longitudinal waves and the s(t,y)-images become even more complex. Further image processing, such as SAFT [9, 10], could possibly be used to identify the signals.

Two other aspects of cracks in metals are the anisotropy of the material and crack closure due to the plastic zone at the crack tip [11, 12]. In this work the Al-Li alloy was considered to be isotropic, because the anisotropy factor is very low [13]. But for materials with higher anisotropy, e.g. steel, the dependence of the wave speed on the orientation of the grains has to be considered for the determination of the crack depth. Crack closure may change the measured crack depth acoustically, because only diffracted signals from the end of the open crack segment may occur, and the depth determined
from the s(t,y)-image will be too small. Therefore, it may be necessary to strain the specimen during the acoustic depth measurement in order to open the crack completely. Indeed, in some preliminary experiments to investigate this, we were able to see the effect of crack closure when we applied a load to the specimen.

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REFERENCES