The analysis of diffraction effects of acoustic waves on the crack's top

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Diffraction effects and features of acoustic wave propagation in elastic media with microcrack were investigated in detail for pulse probing signals. The crack's plane was oriented across the direction of longitudinal ultrasonic wave incidence so that the detection of such a crack with so "inconvenient" spatial location is difficult enough by using traditional acoustic techniques. By using laser interferometer, the set of instantaneous pictures of acoustic field on the specimen's surface, corresponding to different time moments was obtained what allowed investigating and visualizing of acoustic field propagation and diffraction effects on the crack's top in dynamics. Using numerical modeling of diffraction processes of acoustic waves by the crack's edge and top for pulse signals the origin of V-like structures on the snapshots of acoustic fields was explained and analyzed.

1 Introduction

The presence of crack in the material sufficiently affects the elastic wave propagation and gives rise to interesting effects of elastic waves scattering by crack's top and edge which are dependent on the crack's orientation and size. The investigation of elastic wave propagation in solids with crack is one of the actual problems of physical acoustics.

Meanwhile, crack-like flaws are the most dangerous defects – from the critical size, which is very small in many cases, cracks tend to grow rapidly resulting in total catastrophic failures of objects and constructions. Thorough investigation of the mechanism of ultrasound wave interaction with microcrack in solids can find important application in developing new non-destructive testing techniques.

The problem is that the detection of crack with very small width (about 1000 times smaller than ultrasonic wavelength) and with unknown or "inconvenient" location in tested material can be difficult by using traditional acoustic techniques. Signals diffracted from crack's top and edge are of much lower amplitude and can differ by tens of decibels as compared to amplitude of reflected signals. Because of the low amplitude and the high noisy background, diffracted signals may become indistinguishable by using conventional ultrasonic transducers.

An optical detection of ultrasound, such as the laser interferometry technique, gives non-contact, sensitive inspection method that makes possible the spatial distributions of acoustic fields on the metal surfaces to be visualized at different time moments and changes in material response over periods less than wave period to be fixed [1].

The purpose of this paper is to investigate the processes of elastic wave diffraction by crack's top and edge in dynamics using the laser interferometry technique.

2 Experimental method

In this paper, the processes of acoustic field propagation in elastic media with crack in steel block were investigated by using laser interferometer technique. The crack plane was oriented across the direction of longitudinal ultrasonic wave propagation (Fig. 1). Also, the crack is assumed to be very thin with the width of the center part about 4-5 **μ**m (Fig. 2). Detection of such a crack with so "inconvenient" spatial location is difficult enough by using traditional acoustic transducers.

With the use of laser interferometer, the set of instantaneous pictures of acoustic field on the specimen's surface (snapshots), corresponding to the first pulse *i. e.* the wave that has traveled through the sample once in the forward direction, was obtained. Longitudinal ultrasonic waves were excited in the sample by piezoelectric transducers with a resonance frequency of 5 MHz. The transducer's plate was 5 mm in diameter. To detect acoustic fields on the specimen surfaces the OFV5000 Doppler laser interferometer produced by "Polytec" was used.

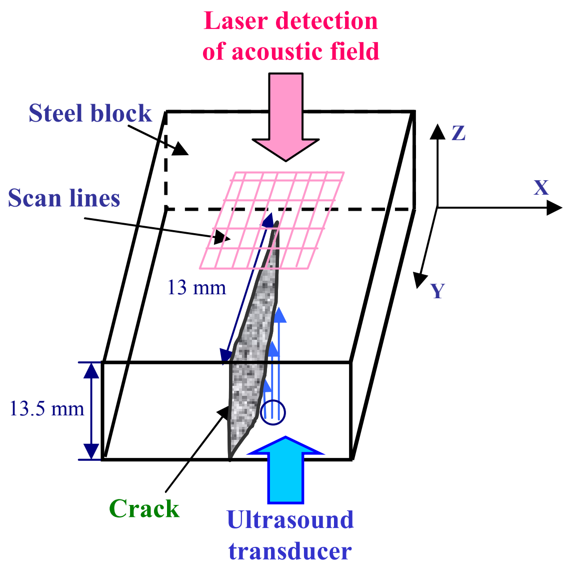

Fig. 1. Specimen geometry for steel block with crack: crack's location in the steel block and the sketch of acoustic field detection.

The piezoelectric transducer was placed on one flat surface of the steel block; the other surface polished so that the roughness did not exceed 4μm was illuminated by a laser beam to detect the acoustic fields (Fig. 1).

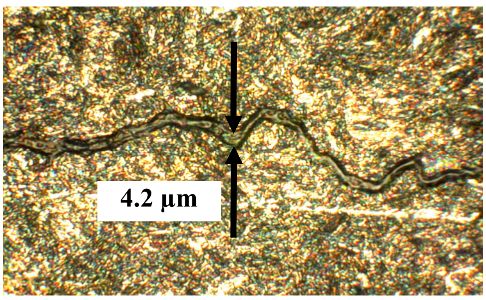

Fig. 2. Microphotograph of the crack's center (x100).

In every point of the scanned area the output type-A scans that are the time dependences of particle velocities had been recorded and digitized by oscilloscope LeCroy 9361.

By scanning the specimen surface within the frame of the scanned field equals to 12×12 mm and typical scanner increment about 0.06 mm, the instantaneous spatial field distributions were obtained on the specimen surface as a function of time in snapshot mode (Fig. 3). The time interval used for capturing such snapshots of acoustic fields was much less that the wave period.

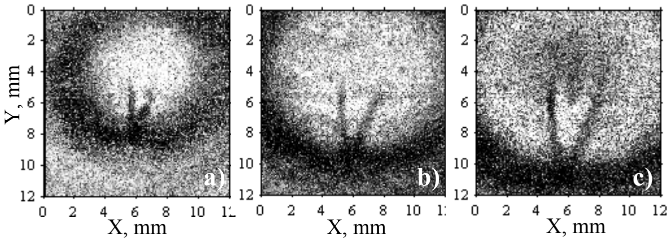

Fig. 3. Snapshots of acoustic field on the specimen surface obtained at time points: 3.0625 µs (*a*), 3.175 µs (*b*) and 3.2625 µs (*c*), corresponding to the first echo-pulse.

Using snapshots of acoustic fields on the specimen surface makes possible thorough investigating acoustical field structure in dynamics with high time resolution. Fig. 3 clearly shows the V-liked structures, which represents the projection of the resulting wave surface, formed due to diffraction effects of acoustic waves by the crack's top. It's interesting to clear out the origination of such V-like structures.

3 Results processing and analysis

Geometrical parameters of the V-like structures and corresponding radii of ultrasonic beam projection on the detection plane at different time moments are shown in Fig. 4.

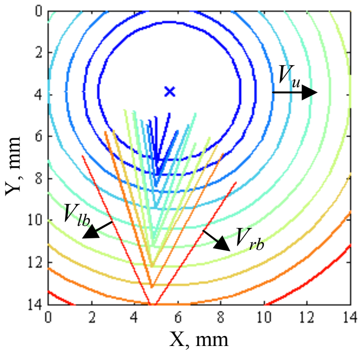

Fig. 4. The V-like structures and corresponding radii of ultrasonic beam projection at different time moments.

As it can be seen from Fig. 4, the V-like structures strictly "follow" the ultrasonic wavefront, with their exit point always locating on the outer contour of ultrasound beam projection. From Fig. 5 it's seen that the time of V-like structures appearing concurs with the maximum of first ultrasonic echo-pulse.

Phase velocity of propagation of ultrasonic beam projection V_u along the detection plane together with phase velocities of right and left branches of V-like structures divergence (V_{rb} and V_{lb}, Fig. 4) are presented in Fig. 6.

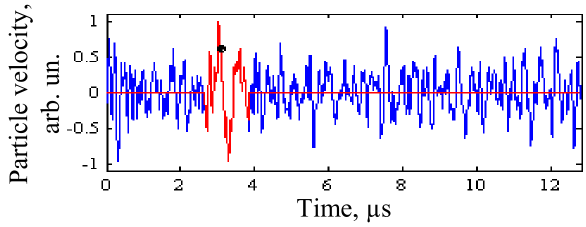

Fig. 5. A-scan of particle velocities corresponding to the point at X=6 mm; Y=8 mm: red lines present time interval corresponding to first echo-pulse, black circle presents the time moment of V-like structures appearing.

As it can be seen, phase velocity of propagation of ultrasonic beam projection V_u is about 10-12 km/s while phase velocities V_{rb} and V_{lb} of right and left sides of V-like structures branching off are not above 4 km/s. Due to such sufficient difference in values of phase velocities the V-like structures resemble the projection of particular complex wave type formed due to the diffraction of incident longitudinal wave by the crack's top.

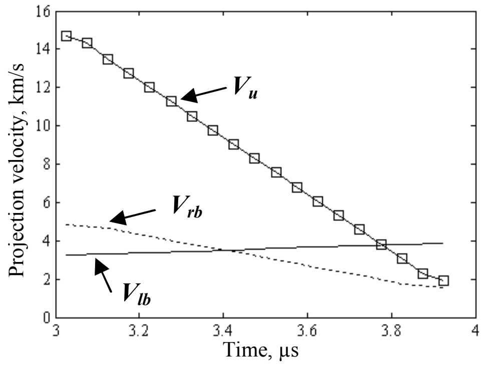

Fig. 6. Phase velocity V_{rb} and V_{lb} of right and left sides of the V-like structures branching off and velocity V_u of ultrasonic beam projection propagation along the detection surface.

To interpret acoustic signals from crack and explain the V-like structures origination the analysis of diffraction of elastic waves by a semi-infinite plate was performed.

The investigation of acoustic wave diffraction by a half-plane crack can be found in many works [2-6]. Keller's geometrical diffraction theory can be used to analyze the results of diffraction of ultrasonic waves by semi-infinite plane [4]. Using photoelastic visualization, Hall [5] has shown the description of crack diffraction and cylindrical diffracted wave formation. Accordingly to Ogilvy in case of elastic wave impinging on a crack, there are four possible responses [6]:

1) wave straight through the crack edge or tip;
2) reflected wave from the crack faces;
3) Rayleigh waves travelling along the crack's edge and radiating when reaching the crack tip;
4) diffracted cylindrical or cone-shaped waves from the crack tip (fig. 7).

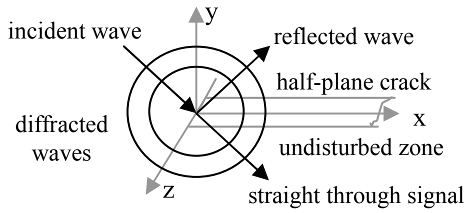

Fig. 7. Diffracted, reflected and straight wave formation in case of elastic wave impinging on a crack's edge according to Ogilvy.

Using simple calculations it's easy to conclude that the V-like structures are not the result of Rayleigh or head waves formation. In the case of Rayleigh wave excitation and subsequent lateral waves reradiating at every point of the edge we need to watch the V-structures appearance at the time moment of about 5.2-5.6 µs on obtained A-scans (Fig. 5). To watch the head wave we need to provide ultrasonic longitudinal wave incidence at 1st critical angle to the crack's edge, with the second medium having higher acoustical impedance. In our case it's impossible as the second media is gas which fills the crack.

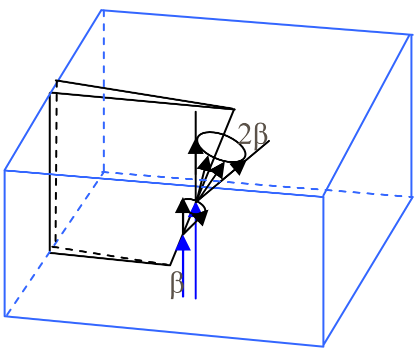

Fig. 8. The sketch of cone-shaped diffracted wave formation on the crack's edge in steel block.

As incident wave impinges the crack's edge at angle β the resulting diffraction waves will have cone-shaped form according to Henl [7]. When crossing the detection plane the projection of cone-shaped diffracted wave gives rise to V-like structures appearing.

To check this assumption we used the equation for scalar potentials of resulting acoustic wave field in case of diffraction on a crack's edge for near-field zone.

For infinite-plane incident waves and the semi-infinite crack's plane the equation for scalar potentials of acoustic wave field according to Born's and Henl's equations [7] will be:

$$P(x,y,z,t)=\frac{\exp(-\frac{1}{4}i\pi)\cdot\exp(-i(\omega t+kz\cdot\sin\beta))}{\sqrt{\pi}}\left[\exp(-ikr\cdot\cos\beta\cdot\cos(\theta-\alpha))\cdot F(-\sqrt{2kr\cdot\cos\beta}\cdot\cos\frac{(\theta-\alpha)}{2})-\exp(-ikr\cdot\cos\beta\cdot\cos(\theta+\alpha))\cdot F(-\sqrt{2kr\cdot\cos\beta}\cdot\cos\frac{(\theta+\alpha)}{2})\right] \quad (1)$$

Here, exp(-iωt) – is the time-factor, $F(a)=\int_a^{\infty}\exp(i\mu^2)d\mu$ - is Frenel's integral, θ=[0;2π] – coordinate angle of cylindrical coordinate system, k – longitudinal wave number, α, β – angles of incidence relative to X and Z axes (fig. 8), $r=\sqrt{x^2+y^2}$ - radius-vector of the point of view.

If we consider that incident wave has nearly spherical wavefront then the resulting field on the detection plane will be determined as the sum of fields calculated for the incident waves with varying angles of incidence α and β. It should be also noticed that only the diffraction of the longitudinal wave without their transformation into shear waves is considered in numerical calculations.

Solutions to the diffraction of elastic waves by crack in steel specimen were numerically calculated and presented in fig. 9.

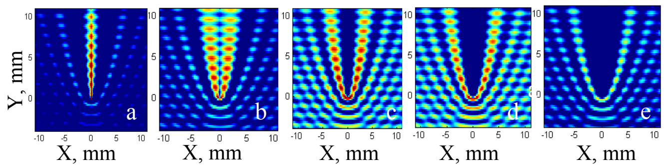

Fig. 9. Solutions to the diffraction of elastic waves by crack in steel specimen for harmonic probing signal with central frequency f=5 MHz at different time moments: (a) t=T/6; (b) t=T/2; (c) t=2T/3; (d) t=5T/6; (e) t=T.

Comparisons between the numerical results and the experimental data show good agreement. The detailed analysis of the wave field structure revealed that the main mechanism of V-structure appearance can be explained by diffraction effects on the crack's edge and top.

Also, to investigate particularities of acoustic signals diffracted from crack a wavelet analysis [8] was used.

For this, the time interval corresponding to first-echo pulse was traced (Fig. 5). Using Sym 8 wavelet functions with four expansion levels a wavelet spectra of coefficients and scalograms, which represent the signal energy, were constructed for A-scans corresponding to the point where V-like structures appear and for distant point from the peripheral region of ultrasound beam (Fig. 10).

As it is can be seen from Fig. 10b, the wavelet spectrum corresponding to the point where the V-like structures appear is more hierarchical and have more levels than the wavelet spectrum for the distant point from the crack (Fig. 10a). This proves that the signal diffracted by crack's top is not a noise but has complicated structure, with frequency components being similar to frequency of acoustic pulse.

By the way, the Fourier spectrum at Fig. 10b doesn't decrease monotonically, there are additional maximum what is described in literature [9] as particularity of signals diffracted from the crack's edge.

This supports that diffraction of elastic waves by the crack's edge and top leads to formation of complicated diffracted wave with particularities discovered on one-dimensional signals (type A-scans) and two-dimensional acoustic field distributions obtained with the use of laser Doppler interferometer.

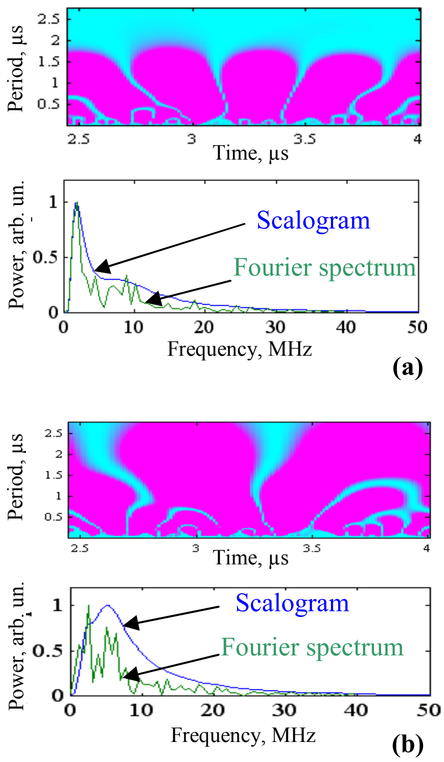

Fig. 10. Wavelet spectra and scalograms corresponding to first-echo pulse: for distant point from the peripheral region of ultrasound beam (a); for a point where V-like structures appear (b).

So, the investigation of the processes of elastic wave interaction with the crack's edge and top allowed us to clear out the mechanism of diffracted wave formation what can be used for developing new ultrasound non-destructive testing techniques.

5 Conclusion

The specialties of acoustic fields of elastic waves diffracted on the crack's edge with "inconvenient" spatial location are visualized with the use of laser interferometer technique.

Time-spatial structure of resulting acoustic field on the specimen surface is defined by the processes of diffraction of elastic wave by the crack's edge and formation of cone-shaped diffracted wave what was proved by numerical modeling of the diffraction field.

The research also highlights that processing algorithms based on wavelet-transform analysis can be effective enough in tracing additional features of signals diffracted by the crack's top and edge.

Thus, the study of wave diffraction pattern may yield information on the nature and orientation of flaws. The results of studying of the acoustic field in dynamics, can find important application in developing new non-destructive testing techniques for detection of cracks of different types.

Acknowledgments

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