Application of ultrasonic surface waves in the detection of microcracks using the scanning heating laser source technique

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This letter reports the application of the scanning heating laser source technique to detect microcracks that may be undetected by conventional methods. In the proposed approach, we monitor changes in the transmitted surface acoustic waves (SAWs) as a heating source is scanned over the crack. The experimental system for microcrack detection by a scanning heating laser source is obtained by exploiting the strong dependence of the transmission efficiency of acoustic pulses on the state of the contacts, whether open or closed, between the crack faces. Microcracks can be detected successfully by confirming the heating position at the point of maximal improvement of the transmission efficiency of the SAWs.

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Microcracks in industrial equipment continuously grow during the machine's operation, leading to the rupture of equipment and causing major accidents. Thus, microcrack detection is a necessary task. Surface acoustic waves (SAWs) are highly suitable for the detection of surface and subsurface defects because of their high sensitivity to such anomalies. Over the years, ultrasonic laser technology has developed into an important branch of nondestructive testing[1−4] because of its significant advantages, which include broadband range, no contact, and remote diagnosis, among others. The scanning laser source technique significantly enhances crack detection, as first presented by Kromine *et al.*[5]. During practical testing, small cracks are often hidden from detection by stronger scattering from other structural irregularities, such as surface grooves, corrosion pits, and coarse grains, all of which actually produced these cracks. Hence, small cracks may be undetectable but should be considered carefully. Nonlinear acoustic technology is an effective tool to improve the resolution of microcrack detection. Buck *et al.*[6] first proposed nonlinear modulation on the interface of samples by external mechanical loading and determined cracks by monitoring second-harmonic signals. This external load is usually applied to the whole sample, likely resulting in additional damage to some parts of the structure. Xiao *et al.*[7,8] reported that the nonlinear modulation of cracks could be achieved using laser radiation such that the thermoelastic stresses brought about by laser heating could partially close the crack. Because temporary thermoelastic stresses disappear after turning off the heating laser, this modulation process is fully reversible and does not cause any damage to the samples. Chigarev *et al.*[9,10] first demonstrated nonlinear frequency-mixing detection of cracks using purely optical methods. High-contrast nonlinear photoacoustic imaging can be achieved by exploiting the strong dependence of the conversion efficiency of photoacoustic waves on the mechanical state of cracks, whether open or closed. Dong *et al.*[11] used a 532-nm continuous wave (CW) laser as an assisted heating source and achieved quasi-static modulation. The location of microcracks can be determined by scanning the excitation and heating sources synchronously.

In this letter, we report a method to detect real surface-breaking cracks by scanning with a heating laser source. When the crack region is irradiated by a laser, thermoelastic stresses induce relative displacement of the two crack faces, partially closing the crack. Transmitted SAW signals are affected significantly by the state of the crack, and the crack can be located by monitoring the amplitude of transmitted SAWs. The change in signals is mainly caused by the nonlinear effect of tension and compression stresses on the interfacial stiffness between the opposite faces of the partially closed crack, while other scatters, including those from fully open large cracks, are eliminated. We also determine the relative displacement of crack faces caused by laser heating using the finite element method (FEM) and compare the calculation results with the experimental ones.

The experimental setup is schematically shown in Fig. 1. A Q-switched Nd:YAG laser with a pulse duration of 1 ns, a pulse repetition rate of 100 Hz, and a wavelength of 1 064 nm is used to generate ultrasound waves. The incident laser beam is focused on a line source 5-mm long and 300-μm wide. We use a 532-nm wavelength CW diode laser to achieve regional heating; the power of the heating laser is 400 mW. The heating laser propagates through an optical fiber with a diameter of 500 μm. Some of the pulse laser energy is scattered by a beam splitter and received by a photodiode as the trigger signal of the oscilloscope. SAWs excited by the pulse laser are propagated through the crack region and detected by the PVDF transducer (the width of the PVDF film is approximately 3 mm). The head of the optical fiber is mounted on a translation stage to facilitate heating of the sample surface at different positions.

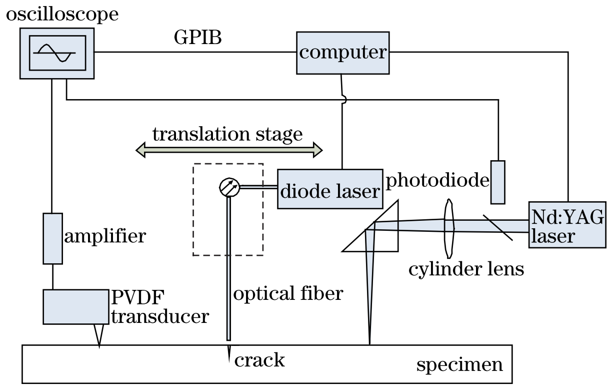

Fig. 1. Experimental setup.

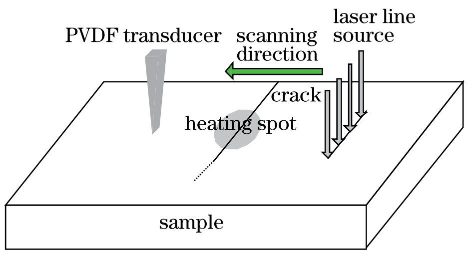

Fig. 2. Schematic diagram of the crack showing excitation, heating, and detection locations.

The excitation and detection points are fixed at a distance of 22 mm in this experiment and are located at both sides of the crack, as shown in Fig. 2. The excitation point is maintained at a significant distance away from the crack to avoid thermal influences on the crack coming from the excitation laser. The heating laser is scanned from one side of the crack to the other with a step length of 62.5 μm; the total scanning distance is 4 mm. The sample used in the experiment is a 50×25×3 (mm) black glass plate that absorbs light strongly. A single plate-breaking crack is prepared by thermal shock.

With the heating source located at the origin, we record SAW signals as *Sigcool*. The heating laser is then turned on for a few seconds, and the SAW signals are impacted and recorded as *Sigheat*. After obtaining the difference between *Sigcool* and *Sigheat*, different value signals (D-signals) $\delta Sig1$ are determined at the current scanning position. This step is repeated n times until we obtain the last D-signal $\delta Sign$. To enhance the signal-to-noise ratio (SNR), D-signals are operated using the formula $\delta_{sig} = \frac{1}{n}\sum_{n}\delta_{sign}$.

The experiment is performed by initially locating the heating source above the center of the crack region. The detected *Sigcool* and *Sigheat* are presented in Fig. 3(a), which shows that the amplitude of *Sigheat* is clearly greater than that of *Sigcool*. Given that the heating beams are different distances away from the crack center, the quantity of heat received by the crack significantly varies. Four heating points are selected for comparison. Point A is located directly over the crack, whereas points B, C, and D are 0.25-, 0.5-, and 0.75-mm away from the crack, respectively. The experimental results are presented in Fig. 3(a), which shows that the amplitude of *Sigheat* A is significantly larger than those of other locations. When point A is irradiated, the crack receives the highest quantity of heat and the thermoelastic stresses generate the largest rate of partial closure, resulting in the largest amplitude of transmitted SAWs. As the heating source is moved farther away from the crack, laser-assisted heating exerts a weaker influence on the crack and the amplitudes of the transmitted SAWs decrease. The partial closure of cracks brought about by laser-assisted heating reduces the reflection of SAWs propagating through the crack.

D-signals acquired from the four heating points are illustrated in Fig. 3(b). The amplitude of D-value A is the largest among the values obtained. As the heating sources are located farther away from the crack center, the amplitudes of the D-signals decrease. Interestingly, although point D is heated 0.75-mm away from the crack, D-signals could still be observed. This phenomenon is likely due to the thermodynamic properties of the black glass. Compared with metal, black glass more strongly absorbs laser irradiation because of its deeper penetration depth (approximately 300 μm)[12], low thermal diffusivity, and low thermal conductivity, among others. In this specimen, temperature gradients and the resulting thermoelastic stresses continue to accumulate during laser irradiation and help partially close the crack.

The experimental results show that partial closure mainly induces amplitude changes in the transmitted SAWs. Thermoelastic stresses are related to the distance between the heating point and the crack. Given the varied distances of heating, partial closure of the crack varies significantly different, which influences the amplitude of the transmitted SAWs directly. Hence, we can determine the exact location of a crack by scanning the laser heating source. The scanning figure of D-signals obtained when the laser is scanned perpendicular to the crack is shown in Fig. 4. The peak amplitude of D-signals changes according to the different heating points. No evident D-signals are found at scanning locations before 1 250

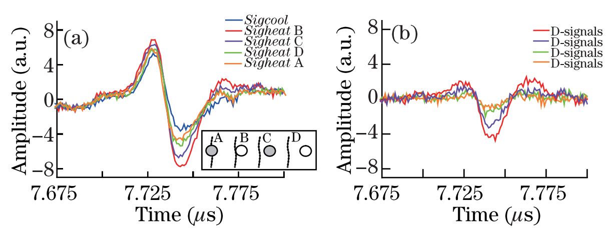

Fig. 3. (Color online) (a) *Sigheat* signals and (b) D-signals under four heating locations.

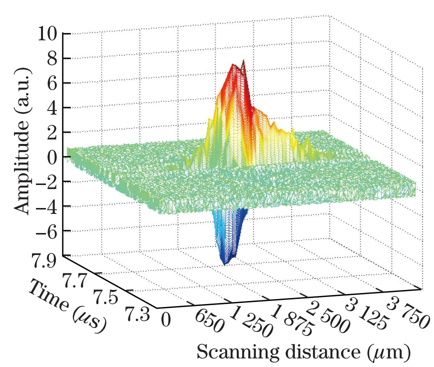

Fig. 4. (Color online) Scanning D-signals.

μm. The amplitudes of the D-signals increase gradually from 1 250 to 1 875 μm because the laser heating begins to exert an impact on one of the crack faces and induces its displacement. After 1875 μm, the amplitudes of the D-signals increase rapidly and reach a maximum at 2 200 μm. At this point, the heating source is directly above the crack and the transmission efficiency of SAWs is highest. The amplitudes of D-signals decrease continuously and cannot be observed after 3 100 μm. During the scanning process, we move only the laser heating source and keep other conditions constant to ensure that the changes SAW signals are only caused by the closure of the crack. Therefore, the D-signals are distributed symmetrically with the crack as the center of symmetry. We can thus conclude that the location of maximum D-signals is identical to the location of the crack center.

The peak-to-peak amplitude of *Sigheat* can also be used to determine the location of the crack. The peak-to-peak curve of *Sigheat* is shown in Fig. 5. As analyzed from the D-signal distribution in Fig. 4, when the heating source is directly above the crack, the amplitude of transmitted SAWs reaches a maximum. Thus, the location of the maximal peak-to-peak value is identical to the location of the crack. Compared with the method that uses the D-signal scanning figure to locate cracks, the peak-to-peak curve of *Sigheat* shows the superimposed signals of positive and negative peaks, which can be used to determine crack locations more clearly and accurately.

FEM is an efficient tool with which to investigate the relative motion of the crack faces caused by laser heating[13]. We build a geometric model as shown in Fig. 6. The crack is set as a simplified V groove with an opening width of 2 μm and depth of 100 μm, and SiO_2 is selected as the model material. The red region in Fig. 6 demonstrates the thermal expansion of the crack qualitatively. The heating source is initially positioned 450 μm from the left side of the crack. Using a scanning step length of 50 μm, the relative displacement of the two crack faces is calculated at 19 different heating positions.

The relative displacement is defined as the sum of the absolute value of the horizontal displacements of the two faces. We set the maximum relative displacement to 1 and consider all other values as relative values. As shown in Fig. 7, no obvious relative displacement in heating positions from –450 to –300 μm can be found. After the heating source passes over the –300-μm position, the relative displacement increases rapidly and reaches a maximum when the heating source is located directly above the crack. As shown in Fig. 5, the peak-to-peak value of *Sigheat* changes significantly between steps 8 and 18. If a step is 62.5-μm long, the corresponding length between steps 8 and 18 is 625 μm. A similar phenomenon can be observed in Fig. 7, which shows the relative displacement of two crack faces changing rapidly from –300 to 300 μm. Given that the diameter of the optical fiber used in the experiment is 500 μm, the diameter of the heating spot is approximately 500 μm. The peak-to-peak value of *Sigheat* and the relative displacement begin to change obviously when the heating source is about to come into contact the crack and recover to previous values gradually after the heating source is removed from over the crack. Experimental and theoretical results both demonstrate that the region obviously affected by laser-assisted heating is approximately 100 μm wider than the size of the heating spot, which may be attributed to the induction of the laser of an additional region that exhibits thermal diffusion efficiently.

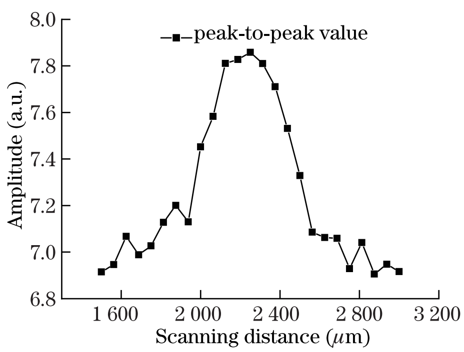

Fig. 5. Peak-to-peak values of *Sigheat*.

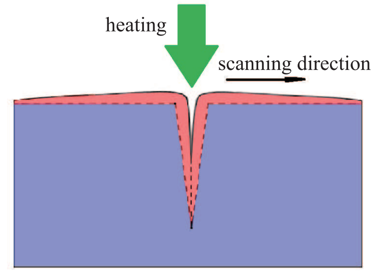

Fig. 6. (Color online) Geometric model of FEM.

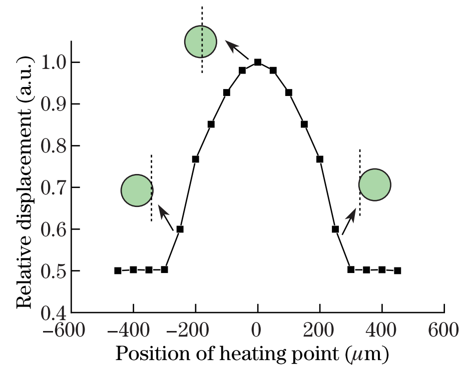

Fig. 7. Relative displacement of crack faces.

In conclusion, we discuss the partial closure of microcracks upon irradiation by a heating laser. The method of microcrack detection by a scanning heating laser is presented. When a crack region is heated, thermoelastic stresses result in partial closure of the crack. We can determine changes in a crack by monitoring the amplitude of transmitted SAWs. When the heating source is located directly above the crack, the crack receives the highest amount of heat and the relative displacement of crack faces reaches a maximum. At this point, the highest amplitude of the detected transmitted SAWs signals is obtained. In the experiment, we scan the heating laser at fixed ultrasonic wave excitation and detection points to rule out interfering effects on the crack produced by the excitation laser and more effectively detect the crack. The relative displacement of crack varies with the heating position, and the peak-to-peak value of *Sigheat* changes with the scanning position consistent with each other.

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