JOURNAL OF APPLIED PHYSICS VOLUME 83, NUMBER 12 15 JUNE 1998

Enhanced ultrasonic detection of fatigue cracks by laser-induced crack closure

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(Received 9 February 1998; accepted for publication 20 March 1998)

Fatigue cracks are usually initiated by small geometrical irregularities or material inhomogeneities that give rise to sharp local stress concentrations. In the early stages of fatigue, small cracks often remain hidden from conventional ultrasonic detection by stronger scattering from the very same structural imperfection that produced them in the first place. A new experimental method was developed to selectively increase the sensitivity of ultrasonic echographic techniques for such hidden fatigue cracks by exploiting one of their most characteristic features, their susceptibility for closure under compressive stress. Thermo-optical modulation by pulsed infrared laser irradiation was introduced to produce a temporary compressive thermal stress on the surface of the specimen. The resulting dynamic closure of microcracks was detected by a high-frequency ultrasonic surface wave technique. It is demonstrated that this method can be used to effectively distinguish fatigue cracks from other structural imperfections present in the material. © *1998 American Institute of Physics.* [S0021-8979(98)09312-8]

I. INTRODUCTION

Positive identification of small fatigue cracks presents a challenging problem during nondestructive testing of fatigue damaged structures. First, it is important to distinguish fatigue cracks from primary geometrical features (e.g., nearby holes, corners, and edges) and secondary irregularities (e.g., uneven machining, mechanical wear, corrosion, etc.). Second, it is important to distinguish small fatigue cracks as early as possible after crack initiation from intrinsic material inhomogeneities such as coarse grains, anomalous microstructure, second phases, precipitates, porosity, various types of reinforcement, etc. The detection threshold of any given nondestructive inspection system, together with the crack growth rate and the critical crack size, determine the minimum frequency of inspection necessary to prevent structural failure. An ever increasing demand for earlier detection of fatigue damage is fueled by the fact that small cracks have been found to grow at unexpectedly high growth rates well below the large crack threshold in aluminum, aluminum–lithium, and titanium alloys.[1] For example, extensive multiple-site fatigue cracking may develop in airframe structures before it can be reliably detected by any of the currently available nondestructive evaluation techniques.[2] Under laboratory conditions, a great variety of nondestructive evaluation (NDE) techniques are available for early fatigue damage detection and characterization. These techniques include acoustic emission, linear and nonlinear ultrasonics, vibration analysis, eddy current inspection, magnetics, thermal imaging, x ray, etc. Three novel NDE techniques, namely holographic interferometry, structural integrity monitoring, and laser ultrasonic inspection, which allow simultaneous detection of numerous small (less than 1 mm) cracks over a large area, have been reviewed recently.[3] Laser ultrasonics in particular has been recognized as one of the most promising ways for future applications due to its noncontacting and remote nature.[4] Unfortunately, all of these techniques tend to lose sensitivity when adapted to in-field inspection of large, complex structures or *in situ* monitoring of a fatigue test.

To a large degree, this insensitivity is due to the fact that fatigue cracks are usually initiated by small geometrical irregularities or material inhomogeneities that give rise to sharp local stress concentrations. In the early stages of fatigue, small cracks often are hidden from ultrasonic detection by stronger scattering from the very same structural imperfection that produced them in the first place. In other words, small fatigue cracks are undetectable not necessarily because the scattered wave they produce is weak in an absolute sense, but because it is weak relative to other signals produced by inherent inhomogeneities such as the coarse grain structure. Various signal processing techniques have been studied in order to reduce this inherent material noise, including split spectrum processing,[5] cut spectrum processing,[6] wavelet transform technique,[7] etc. However, since these techniques are all based upon the nonspecular properties of grain scattering, they can only be used efficiently when the grain size, or more generally the characteristic dimension of the competing microstructural feature, is orders of magnitude smaller than the targeted fatigue crack, which is not the case in many aerospace materials with relatively coarse grain structure like titanium alloys. Furthermore, in most practical applications the weak fatigue crack signal competes with a single, large artifact when the anomalous reflector is comparable or larger than the acoustic wavelength. It should be mentioned that the more recently developed neural network technique provides another way to identify fatigue cracks.[8] It is actually another kind of signal processing technique using flaw classification algorithms instead of direct filtering at the cost of much more intensive computations.

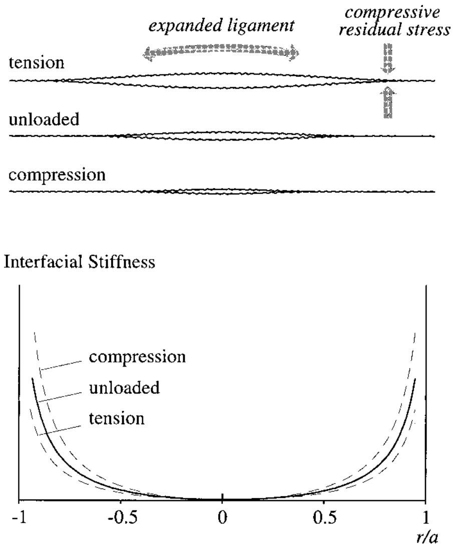

FIG. 1. Schematic illustration of crack closure as parametric modulation of the interfacial stiffness by the changing normal stress.

II. CRACK CLOSURE

Generally, linear acoustic characteristics (attenuation, velocity, backscattering, etc.) are not sufficiently sensitive to very small fatigue cracks. On the other hand, it has been noted that in a great variety of structural materials even very small fatigue damage can produce very significant excess nonlinearity, which can be orders of magnitude higher than the intrinsic nonlinearity of the intact material.[9] The excess nonlinearity is produced by the strong local nonlinearity of a microcrack whose opening is smaller than the particle displacement. There are two basic types of nonlinear phenomena that can be exploited for enhanced crack detection. In the so-called harmonic generation method a narrow-band, high-amplitude ultrasonic vibration itself produces sufficient particle displacements on the surface of the crack, that result in partial temporal crack closure, which in turn exhibits itself in the generation of second, third, and higher harmonics of the fundamental ultrasonic frequency in the reflected and transmitted waves.[10,11] In the so-called acousto-elastic method the low-amplitude ultrasonic vibration itself produces but negligible particle displacements on the surface of the crack while a static or very slow quasi-static external load is applied to produce the high-amplitude elastic deformation required for partial crack closure.[9] In this study we shall consider a variation of this acousto-elastic technique, when the partial crack closure is conveniently produced by localized thermal stresses.

Figure 1 shows the schematic diagram of a partially closed fatigue crack under varying normal stress. The center of the fatigue crack is usually open due to the plastic elongation of the ligament connecting the tips that occurs during the nucleation and growth of the crack. At the same time, the tips of the same crack are usually tightly closed by compressive residual stresses resulting from the same plastic deformation. The temporal modulation of the ultrasonic scattering from such a partially closed fatigue crack under varying normal stress can be interpreted in two ways. According to the simpler approach, it is only the size of the open fraction of the crack that increases and decreases under tensile and compressive normal stresses, respectively. Actually, the transition between the open and closed parts is more continuous. According to more realistic models of crack closure, the stiffness of the interface contact between the opposite surfaces of the crack undergoes a parametric modulation by the changing normal stress, as it is shown in Fig. 1. In the compression phase, the interfacial stiffness becomes increasingly high as the crack becomes tightly closed. In contrast, in the tension phase, the interfacial stiffness approaches zero as the crack becomes fully open. The parametric modulation of the ultrasonic scattering from the crack is caused by the stress dependence of the interfacial stiffness between the opposite faces of the fatigue crack. The resulting nonlinearity is zero for both entirely open and entirely closed cracks. Due to local residual stresses in the material, typical fatigue cracks are partially closed when the external load is removed and generate strong excess nonlinearity via crack closure. This effect can be exploited through different ways to significantly improve the detectability of small cracks.

Perhaps the simplest way to observe crack closure under laboratory conditions is to ultrasonically monitor the opening and closing of fatigue cracks when subjecting the specimen to static or quasi-static external loading. The technical realization of the acousto-elastic method must incorporate two tasks. One is to find an effective way to generate crack closure in the specimen, i.e., the ''elastic'' problem. The other is to find a way to monitor the resulting parametric modulation by ultrasonic means, i.e., the ''acoustic'' problem. The modulation stress may be generated through different ways such as external cyclic loading in a typical fatigue test[9] or exploiting the inherent vibration of the structure itself during operation.[12] The main disadvantage of using external mechanical loading is that usually the whole structure must be loaded, which requires very substantial forces and might cause additional damage in certain parts of the structure. More localized temporary stresses can be produced by simply cooling or warming the specimen to be tested[13] as we are going to demonstrate later.

In order to detect and quantitatively measure the resulting parametric modulation, the detected ultrasonic wave form can be processed and analyzed by different methods depending on the degree of modulation. The simplest asynchronous method is based on signal differentiation achieved by continuously subtracting from the detected wave its most recent running average taken over a few seconds.[13] Such simple signal processing is readily available on most state-of-the-art digital flaw detectors. However, the asynchronous method cannot distinguish between the periodic modulation caused by cyclic loading and the essentially random extraneous modulation caused by artifacts such as thermal drift or material creep. Much better selectivity can be achieved by phase-sensitive synchronous detection when only variations maintaining a constant phase relation with the excitation signal over a long integration period are measured. The schematic diagram of phase-locked synchronous detection of crack closure is shown in Fig. 2. As an example, Fig. 3 shows the effects of ordinary asynchronous time-averaging

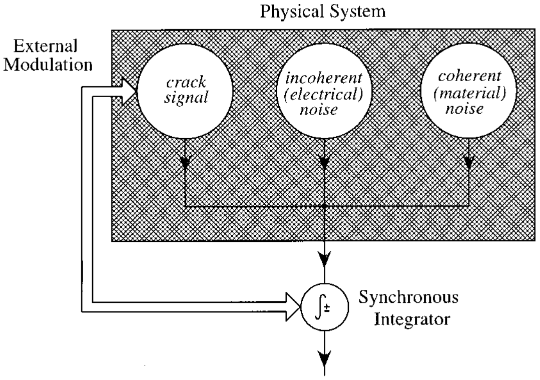

FIG. 2. Schematic diagram of phase-locked synchronous detection of crack closure.

and synchronous (phase-locked) time-averaging on the detected signal.[13] Ordinary time-averaging routinely used in digital ultrasonic flaw detectors eliminates only the truly incoherent electrical noise without discriminating between fatigue cracks and artifacts. In comparison, synchronous detection also eliminates time-invariant artifacts by alternating the sign associated with the detected signal before averaging depending on whether it was taken during crack opening or closure. The only retained phase-locked dynamic component is the difference of the reflected echoes from the tip of a fatigue crack in its closing and opening states. This signal is mainly caused by the nonlinear effect of tension and compression stresses on the interfacial stiffness between the opposite faces of the partially closed fatigue crack, while other scatterers, including fully open large cracks, are eliminated.

It should be mentioned that this kind of synchronous modulation has also been used successfully in some other kinds of nondestructive testing techniques such as eddy current inspection[13] and acoustic emission.[14] Furthermore, the nonlinear effect of crack closure could also be exploited through some other ways to increase the detectability of fatigue cracks, such as measurement of ‘‘harmonic mode shapes’’ during vibration[15] and monitoring of strain wave functions under a random load.[16] In fact, any significant change in structural and material characteristics under external deformation can be a telltale indication of fatigue crack somewhere in the structure.

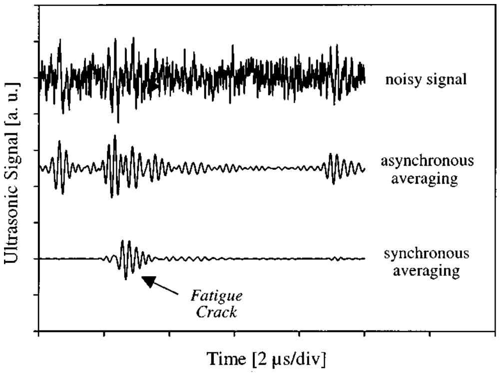

FIG. 3. The effects of ordinary asynchronous time-averaging and synchronous (phase-locked) time-averaging on the detected signal.

TABLE I. List of the fatigue specimens used in this study.

I.D.	Type	Cycle[a]	Length (mm)
Ref.	saw-cut	n/a	3 mm
#9	fatigue crack	1.73×10^5	0.61 mm
#10	fatigue crack	1.69×10^5	1.25 mm
#11	fatigue crack	1.73×10^5	1.75 mm

[a] Maximum load 28.6 ksi, load ratio 0.9, frequency 29 Hz, 2024 Al.

III. DYNAMIC CRACK CLOSURE DUE TO THERMAL STRESSES

As we have mentioned in the previous section, an alternative way of producing dynamic crack closure is by cooling or warming. It is well known that temperature variations can lead to extremely high levels of internal stresses in materials having constituents of different thermal expansion coefficients. For example, in a metal matrix composite strong static stresses can be produced just by slowly cooling or warming the specimen. Of course, the same approach would not work in essentially homogeneous materials such as an aluminum airframe part or a titanium alloy engine component. However, dynamic thermal stresses can still be produced by rapid and concentrated cooling and heating. These stresses are temporary only as they disappear when the temperature gradients vanish due to the thermal conductivity of the material.

The feasibility of producing dynamic crack closure by localized cooling with a commercial freezing spray has been already demonstrated on 2024 aluminum four-point bending specimens.[13] According to our measurements, ~100 W cooling power can be delivered in this way to a small spot of ~0.100 in. diameter. We have used this technique to temporarily deform a series of 6 in.×1 in.× 1/2 in. 2024 aluminum bars containing fatigue cracks (see Table I). The deformation has two principal contributions which can be separated easily based on their different time-dependence. Figure 4 illustrates these two deformations in a schematic way. First, there is an almost instantaneous bending deformation caused by the through-thickness temperature gradient, which can be readily verified by measuring the end displacement of the bar. Second, there is a ‘‘necking’’ deformation caused by the axial temperature gradient, which can be also verified by measuring the internal temperature at the center during and immediately after cooling.[13] During cooling, the temperature decreases rapidly. Afterwards, the temperature increases exponentially with a time constant of ~5 s until it equalizes over the whole length of the specimen. Naturally, there is also an additional, much slower warming as the specimen returns to the ambient temperature via thermal conduction through the surrounding air.

Figure 5 shows the effect of initial crack opening and subsequent crack closure on the ultrasonic reflection from the four specimens listed in Table I. The measurements were made with a 5 MHz surface wave transducer. The cooling spray was applied for ~1.5 s at the opposite side of the specimen. The signal from the reference specimen was strong but remarkably stable. The signals from the other three specimens exhibited a distinctive modulation upon

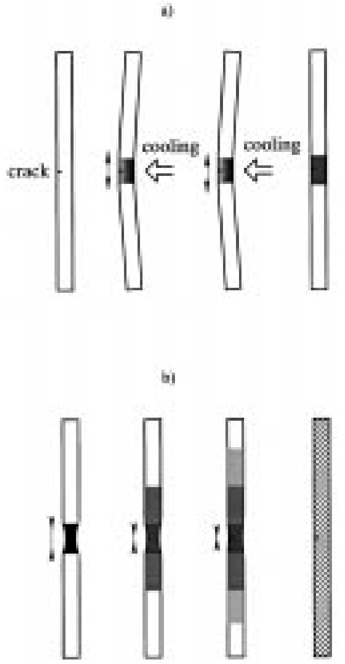

FIG. 4. Initial crack opening (a) caused by bending due to the through-thickness temperature gradient and subsequent crack closure (b) caused by necking due to the axial temperature gradient.

cooling. The characteristic shape of the modulation well corresponds to the expected deformation. First, an instantaneous bending deformation causes crack opening, thereby increasing the ultrasonic reflection from the crack. Later, a subsequent contraction causes a lagging crack closure, thereby decreasing the signal for a substantial time after the cooling. The characteristic modulation of the ultrasonic signal readily reveals the presence of partially closed fatigue cracks in the specimens. It is important to point out that this technique measures the degree of modulation due to crack closure rather than the absolute magnitude of the scattering. This point can be readily demonstrated through the frequency dependence of the measured modulation. Figure 6 shows the amplitude modulation measured on sample #11 at two different ultrasonic frequencies. Although the signal itself increases with frequency, the dynamic modulation due to the thermally induced crack closure is stronger at lower frequency, where the changing interfacial stiffness has a stronger effect on the scattering from the crack.[17]

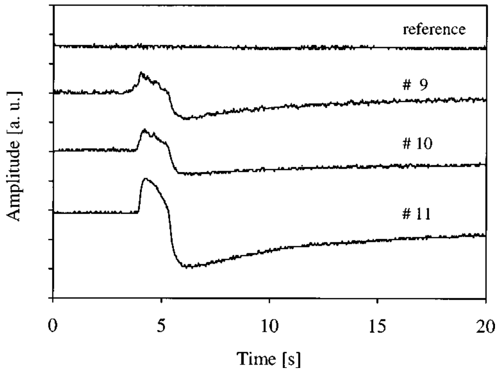

FIG. 5. The effect of initial crack opening and subsequent crack closure on the ultrasonic reflection from four specimens listed in Table I.

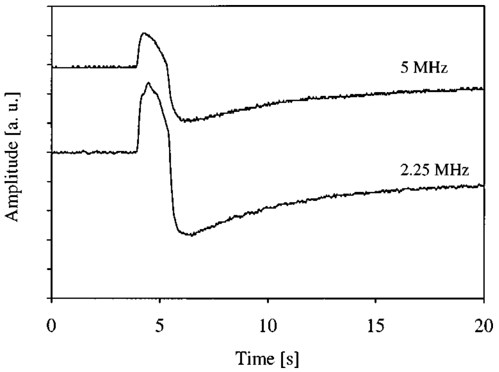

FIG. 6. The effect of the inspection frequency on the strength of the amplitude modulation (sample #11).

Dynamic cooling or warming have numerous advantages over cyclic mechanical loading. For example, mechanical loading can cause instability in the structure and may require complicated fixtures for components of different sizes and shapes. Furthermore, it tends to produce only one-dimensional tension and compression stresses and thus it is difficult to generate crack closure in unknown directions. In contrast, dynamic cooling and warming can generate three-dimensional compression or tension stresses at one time and thus are suitable for detection of fatigue cracks with different orientations. However, in the case of the dynamic cooling method, the cooling spray has to be applied at the opposite side of the specimen in order to avoid its strong attenuating effect on the ultrasonic Rayleigh wave propagating along the surface of the specimen. Additional limitations of this technique are associated with modest cooling power available from commercial sprays, the difficulty of concentrating the spray over a small spot, and the inherent variability of the produced cooling. In comparison, laser irradiation can easily overcome these limitations, thereby offering a better alternative for increasing the sensitivity of ultrasonic detection of fatigue cracks by dynamic crack closure.

IV. THERMO-OPTICAL MODULATION

In the following we investigate the possibility of using laser irradiation to produce dynamic crack closure. Laser ultrasonics is a new nondestructive materials characterization technology which combines the ability of ultrasonic inspection with the flexibility of optical methods.[4] This method has already shown its potential in numerous applications for the aerospace industry and other demanding applications. When relatively low-intensity ($<10^6$ W/cm^2) radiation is incident on a metal surface, some of the light energy is absorbed via electrons in the conduction band and converted into heat, while the rest is reflected. The absorbed energy is dissipated within a few nanometers of the surface, producing a rapid rise in temperature. The thickness of the heated layer increases with time as heat is conducted into the bulk of the material. In the case of a short pulse of less than 1 μs in duration, the sudden rise in the surface layer's temperature

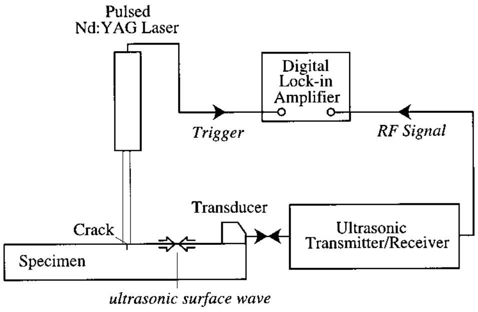

FIG. 7. Schematic diagram of the experimental arrangement with thermo-optical modulation.

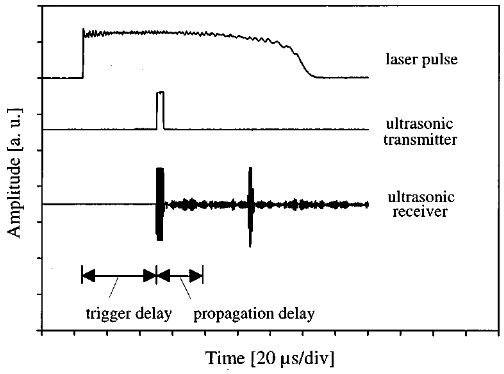

FIG. 8. Sequential diagram of the synchronized optical and ultrasonic pulses.

causes ultrasonic radiation via thermal expansion. By increasing the length of the optical pulse to approximately 100 μs, the direct generation of ultrasound can be eliminated and the resulting thermal stresses can be exploited to produce parametric modulation by dynamic crack closure. Laser irradiation is a rather efficient way to generate crack closure since it is very easy to control and operate while maintaining the noncontact, remote nature of laser ultrasonics. Since it does not produce acoustic loading on the free surface of the specimen, it can be applied directly to the spot to be inspected. Furthermore, the short duration of the heating laser pulse allows us to produce higher temperature gradients, and consequently higher thermal stresses, without significantly warming the specimen.

Figure 7 shows the schematic diagram of the experimental arrangement with thermooptical modulation. The crack is located at the surface of the specimen. The region of interest is continuously monitored by an ultrasonic flaw detector emitting a surface acoustic wave and operating in pulse-echo mode. Surface waves carry most of their energy in a shallow layer of less than one wavelength below the surface, therefore they offer unique sensitivity to near-surface variations in material properties. However, weak reflected signals from small cracks cannot be unequivocally distinguished from scattering from intrinsic inhomogeneities and surface irregularities. Such hidden cracks can be revealed by monitoring the variation of the detected ultrasonic signal as the surface temperature is abruptly increased. The sharp temperature rise produced by laser irradiation is accomplished by a strong temporal compressive stress as the extending ''skin'' becomes too large for the bulk of the material.

In order to optimize the sensitivity of the thermo-optical modulation technique, we have to maximize the temperature gradients causing the thermal stress. This can be achieved by either increasing the total optical power or by reducing the length of the irradiation period, but certain limitations have to be complied with in order to avoid permanent surface damage on the specimen and direct ultrasonic surface wave generation by the induced thermal stresses. We have used a long-pulse Brilliant Nd:YAG laser without Q-switching that produces 120-μs-long pulses of 360 mJ total energy at 1.06 μm near-infrared wavelength at 50 Hz repetition frequency. The detected ultrasonic signal was analyzed by a programmable digital peak detector that assures excellent accuracy and repeatability. The ultrasonic pulser is synchronized to the laser to produce two pulses for each irradiation; one directly following the laser pulse with an adjustable delay of up to 300 μs and the other delayed by a fixed amount of 10 ms. The first pulse interrogates the crack when it is ''hot'' while the second one provides a ''cold'' reference. Figure 8 shows the sequential diagram of the synchronized optical and ultrasonic pulses. Only the ''hot'' ultrasonic pulse is shown which reaches the location of inspection when the compressive thermal stress is maximum. The ''cold'' ultrasonic pulse is launched 10 ms later when the compressive stress has completely diminished and it is not shown in Fig. 8. It should be mentioned that the actual delay between the start of the laser irradiation and the arrival of the ultrasonic pulse at the location of inspection includes not only the adjustable synchronization delay between the laser and the ultrasonic transmitter but also the approximately 20 μs one-way propagation delay from the transducer to the crack.

Figure 9 shows the backscattered ultrasonic echo received from a specimen (#11) which contains a starter notch that is hiding a small fatigue crack and an additional surface scratch made after the fatigue cycling. This measurement was taken at 5 MHz, when both the real and artifact signals were approximately 18 dB above the grain noise. Our main goal here is to demonstrate the ability of the thermo-optical crack-closure technique to unequivocally distinguish real fatigue cracks from comparable artifacts. From this figure we

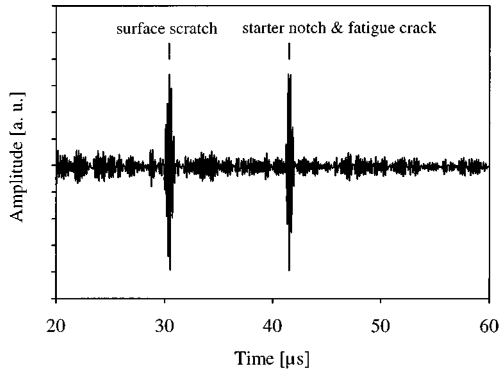

FIG. 9. The backscattered ultrasonic echo received from a specimen (#11) which contains a starter notch that is hiding a small fatigue crack and an additional surface scratch made after fatigue cycling.

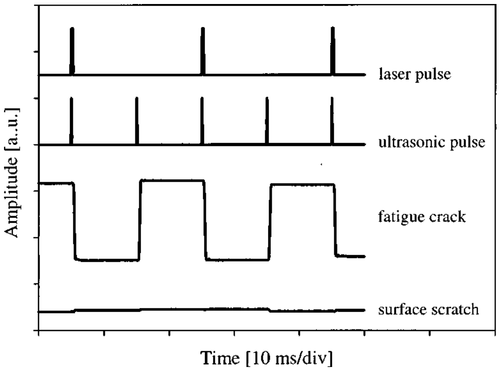

FIG. 10. Identification of a fatigue crack by laser-induced crack closure.

can see that the echo reflected from the surface scratch has almost the same amplitude as the one from the fatigue crack and thus may cause false alarms in conventional inspection. Furthermore, the fatigue crack is partially hidden by the edm starter notch itself that is necessary to initiate the crack. It is rather typical that the geometrical feature or material imperfection that produces the stress concentration, which will ultimately start the fatigue crack, itself produces an ultrasonic echo that is difficult to distinguish from the initially weaker scattering of the fatigue crack.

By applying dynamic crack-closure modulation via pulsed-laser irradiation, the fatigue crack can be identified very easily. Figure 10 shows the different modulation levels for the surface scratch and the fatigue crack. The two traces on the top show that every second ultrasonic signal reaches the inspected area just after laser irradiation, i.e., when the area is ''hot'' and any possible fatigue crack is slightly closed by the resulting compressive thermal stress. The lower two traces show the output of the digital sample-hold unit that measures the peak of the ultrasonic backreflection for every ultrasonic transmission. Clearly, the reflections from the ''hot'' fatigue crack are lower than those from the ''cold'' one. This strong thermo-optical modulation of the ultrasonic signal is uniquely characteristic to partially closed fatigue cracks. In comparison, the modulation associated with the surface scratch is negligible since it lacks those characteristic features that render a real fatigue crack particularly sensitive to dynamic crack closure.

Figure 11 shows the measured amplitude modulation from the same specimen as a function of synchronization delay. Strong crack closure occurs between 40 and 160 μs after the beginning of the laser irradiation. The maximum modulation is approximately 0.06 dB, roughly six times higher than the 0.01 dB standard deviation of individual amplitude measurements done by our digital data acquisition and processing system. Since both hot and cold measurements are continuously refreshed at the 50 Hz repetition frequency of the pulsed laser, the accuracy of the phase-locked synchronous demodulator over a 1 s integration time is as good as 0.0015 dB. It should be mentioned that these measurements were done at 5 MHz and the crack-closure modulation is approximately 60% higher at 2.25 MHz, as it was found in a previous experiment. Furthermore, the modulation can be easily increased by a factor of 4 via blackening the surface with a permanent marker, which increases the otherwise rather low absorption of laser power in aluminum.

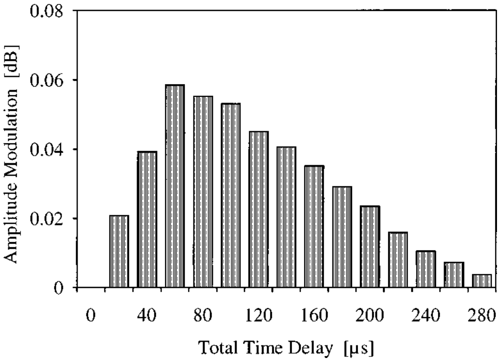

FIG. 11. Measured amplitude modulation from the fatigue crack (#11) as a function of synchronization delay.

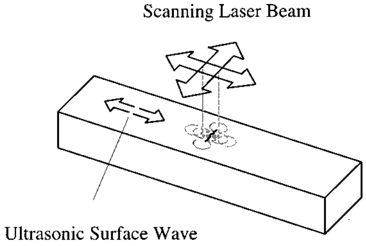

FIG. 12. Scanning of the area to be inspected by the pulsed-laser beam.

The magnitude, spatial extent, and temporal variation of the thermo-optically induced compressive stress depends on a number of material properties including optical absorption, thermal conductivity, specific heat, thermal expansion coefficient, etc. Generally, the affected area where crack closure can be expected is slightly larger than the actually irradiated spot. The localized nature of the induced stress is an important advantage of the thermo-optical modulation by pulsed-laser irradiation over the previously described mechanical loading and cooling methods. The maximum modulation level can be achieved by focusing the laser beam to the smallest spot size that can be maintained on the surface without causing permanent damage. However, a larger diameter laser beam allows us to detect cracks in a larger area without having to focus the laser exactly to the tip of the crack. The received ultrasonic signal contains backscattering information from a long range along the propagation path of the acoustic beam, but only a fraction of this path is actually irradiated by the pulsed laser light. Unless the approximate location of the suspected crack is already known, full coverage of the acoustic path necessitates the axial scanning of the laser beam. Furthermore, the ultrasonic beam is usually significantly wider than the modulating laser beam, therefore some lateral scanning of the laser beam might be also necessary. Figure 12 shows the schematic diagram of how the area to be inspected can be scanned by the pulsed laser beam whenever the total inspection area and the available laser power do not facilitate simultaneous inspection. The actual size of the area where strong crack closure can be expected can be easily determined by experimental means. Figure 13

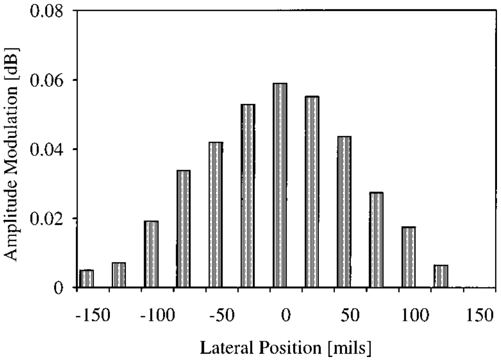

FIG. 13. Variation of the measured amplitude modulation due to thermal crack closure as the laser beam is scanned over the area containing the small fatigue crack.

shows the variation of the measured amplitude modulation due to thermal crack closure as the laser beam is scanned over the area containing the small fatigue crack. The diameter of the active spot where strong crack closure occurs is approximately 0.150 in., about four times the diameter of the unfocused laser beam used to heat the specimen.

V. SUMMARY AND CONCLUSIONS

We have investigated the feasibility of unequivocal discrimination of real fatigue cracks from artifact signals produced by other scattering objects unrelated to fatigue damage based on dynamic crack-closure modulation. We have demonstrated experimentally the feasibility of fatigue crack identification by thermo-optical crack closure in aluminum. By this technique, otherwise dubious flaw indications that are partially or fully immersed in grain and structural noise could be recovered and identified positively without necessarily raising the number of false alarms. It is expected that the sensitivity of the synchronous thermo-optical modulation technique can be further increased by decreasing the optical wavelength so that a larger fraction of the irradiating power can be absorbed in the specimen.

In state-of-the-art flaw detection systems, digital averaging of repetitive A-scans is used to eliminate incoherent electrical noise. Coherent spatial noise caused by coarse grain structure and other inhomogeneities cannot be eliminated in this simple way since it is invariant on each of the A-scans recorded at the same location. We suggest that this microstructural noise can be eliminated, or at least significantly reduced, by synchronous thermo-optical modulation using the well-known lock-in amplifier principle. For example, if every second A-scan is taken with laser irradiation and inverted before averaging, both incoherent electrical and coherent microstructural noises can be rejected with substantial improvement in fatigue crack detectability. By exploiting the unique susceptibility of fatigue cracks to stress modulation we can distinguish them from intrinsic scattering sources such as coarse grains, grain colonies, corrosion pits, fretting, surface scratches, pits, and other topographic features, and we can increase the detectability of fatigue cracks by an expected ratio of one-to-two orders of magnitude. Direct mechanical deformation of the whole structure is usually not practical except during real-time monitoring of fatigue cycling. Even then, the overall mechanical deformation and vibration of the specimen causes instability and artifacts might be mistakenly identified as fatigue cracks. Alternatively, localized dynamic thermal stresses produced by laser irradiation can be used to produce crack closure without adverse deformations and vibrations in the specimen as a whole. Infrared laser excitation offers an attractive way to produce the necessary compressive stresses as the suspected area can be optically scanned while the ultrasonic scattering is monitored by either conventional contact or more sophisticated laser-ultrasonic means.

Like other techniques, the suggested thermo-optical modulation technique also has its limitations. Fully open cracks, which are usually easier to detect by other techniques, do not produce significant crack closure since the produced thermal stress levels are rather modest. Although most fatigue cracks are initiated at or close to the surface, some cracks might also occur deep inside the material. Such cracks could not be detected by ultrasonic surface wave inspection in the first place because of the small penetration depth of the surface wave itself. Furthermore, even if we used bulk ultrasonic waves to interrogate the specimen, optically induced thermal stresses could not be used to produce crack closure at larger depths since they are also limited to the close vicinity of the surface. In order to better understand the range of applicability of our technique, we are currently investigating the depth dependence of the dynamic thermal stresses by finite element simulation. Finally, it should be emphasized that in its present form, the thermo-optical crack closure technique cannot be readily adapted for field inspection to detect flaws at unknown locations. Its main advantage is its unique sensitivity to distinguish real fatigue crack initiation from artifact signals associated with the very structural features that produce the stress concentration which might generate the fatigue crack. For example, it can be used in real-time monitoring of fatigue testing to detect the exact point of crack initiation from a starter notch.

ACKNOWLEDGMENTS

This effort was sponsored by the Defense Advanced Research Projects Agency (DARPA) Multidisciplinary University Research Initiative (MURI), under Air Force Office of Scientific Research Grant No. F49620-96-1-0442.

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