Thermo-optical modulation of ultrasonic surface waves for NDE

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Abstract

The well-known thermo-elastic effect of laser irradiation can be exploited to produce strong localized stresses when an expanded, long pulse, low-intensity laser beam is used to irradiate the specimen. These stresses will produce a parametric modulation of the received ultrasonic signals, that is somewhat similar to the acousto-elastic effect often used in nonlinear ultrasonic studies. It is shown in this paper that otherwise hidden small cracks in fatigue-damaged aluminum and titanium specimens can be readily detected by exploiting this optically induced thermo-elastic modulation during ultrasonic surface wave inspection since they are susceptible to crack closure and therefore exhibit strong parametric modulation. The temporal and spatial variations of the ultrasonic signals due to laser irradiation were evaluated numerically and experimentally. Based on these results, the direct temperature modulation of the ultrasonic velocity can be separated from the thermo-elastic stress modulation present only in cracked specimens. It was found that this method can be used to selectively increase the sensitivity of ultrasonic flaw detection to small fatigue cracks by more than one order of magnitude. © 2002 Published by Elsevier Science B.V.

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1. Introduction

An ever increasing demand for early 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]. It is known that 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]. Fatigue cracks are often initiated by small geometrical irregularities or material inhomogeneities that produce sharp local stress concentrations. As a result, in the early stages of fatigue, small cracks are often hidden from ultrasonic detection by stronger scattering from the very same structural imperfection that produced them in the first place.

The most characteristic feature of fatigue cracks, that can be exploited to positively identify them, is that they are partially closed by residual stresses and the opposite surfaces match each other fairly well so that they can be easily closed or further opened by the application of modest external deformations. 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 crack are usually tightly closed by compressive residual stresses resulting from the same plastic deformation. In order to increase the detectability of such fatigue cracks, we can exploit the parametric modulation of ultrasonic wave scattering caused by the changing interfacial stiffness and effective size of the closing and opening crack.

Perhaps the simplest way to observe crack-closure when subjected to laboratory conditions is to ultrasonically monitor the opening and closing of fatigue cracks when subjecting the specimen to static or quasi-static external loading. This phenomenon is demonstrated in Fig. 1 showing the ultrasonic echograms recorded from an intermittent surface-breaking fatigue crack (length ≈ 0.9 mm, depth ≈ 0.25 mm) in Ti–6Al–4V at 10 MHz. The graphs on the left side show the detected raw rf signals while the graphs on the right side show the processed differential signals, that were obtained by subtracting the baseline signal, which was recorded without straining the specimen. When the surface is smooth, the crack signal is fairly easily detected even in the raw data with a ≈15 dB signal-to-noise ratio. However, when the surface is rough, like in the case of fretted specimens, the...
signal-to-noise ratio drops to \( \approx 0 \) dB and the fatigue crack becomes invisible in the raw data, though it is still readily detectable in the differential signal since the otherwise very strong ultrasonic scattering from surface irregularities is rather insensitive to the presence of local deformations.

Buck and his co-workers were the first to report the parametric modulation of ultrasonic Rayleigh wave reflection and transmission at surface breaking fatigue cracks during mechanical loading of the specimen as indicated by the varying generation of second, third, and higher harmonics of the fundamental ultrasonic frequency [3,4]. The modulating stress may be produced by different means, such as external cyclic loading in a typical fatigue test [5,6] or exploiting the inherent vibration of the structure itself during operation [7]. 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 [8]. In this paper we will review recent results indicating the feasibility of using optically induced thermo-elastic stresses for fatigue crack identification.

2. Thermo-optical modulation

The thermo-optical modulation technique has been recently developed and successfully demonstrated for enhanced fatigue crack detection in aluminum specimens [9]. Fig. 2 shows a schematic diagram of the experimental arrangement with pulsed-laser thermo-optical modulation. The region of interest is continuously monitored by a pulse-echo ultrasonic flaw detector using surface waves. The sharp temperature rise produced by laser irradiation is accompanied by a strong temporal compressive stress as the extending “skin” becomes too large for the bulk of the material. We used a long-pulse Nd:YAG laser without Q-switching that produces 120-\( \mu \)s-long pulses of 360-mJ total energy at 1.06-\( \mu \)m infrared wavelength and 50 Hz repetition frequency.

![Fig. 1. Enhanced ultrasonic fatigue crack detection via crack closure in a Ti–6Al–4V specimen with smooth (a) and rough (b) surfaces.](image)

![Fig. 2. Schematic diagram of the experimental arrangement for thermo-optical modulation.](image)
Depending on the repetition frequency of the pulsed laser and the thermal diffusion time in the material, we can distinguish between two types of modulation. First, there is an essentially instantaneous “dynamic” modulation which is in phase with the repetition frequency of the laser and can be most easily detected by synchronous demodulation of the received ultrasonic signal. This type of modulation is characteristic to materials of high-thermal diffusivity, such as aluminum, in which the temperature gradients and the resulting thermo-elastic stresses quickly disappear after the termination of the laser pulse. Second, there is a much slower “quasi-static” modulation which is an integrated effect of many individual pulses when the laser is turned on for a few seconds or longer and can be most easily detected by asynchronous demodulation of the received ultrasonic signal. This type of modulation is characteristic to materials of low-thermal diffusivity, such as titanium, in which the temperature gradients and the resulting thermo-elastic stresses linger long after the termination of the individual laser pulses and the modulation is greatly amplified by the cumulative effect of subsequent pulses.

3. Dynamic thermo-optical modulation in Al-2024

In order to measure the dynamic modulation in phase with the 50 Hz repetition frequency of the laser, the ultrasonic pulser is synchronized to the laser so that it produces 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 dynamic modulation of the measured signal is caused by the alternating variation of the detected ultrasonic echo between cold and hot states. This modulation is partly caused by direct thermal modulation of the sound velocity in the material and partly by thermal stresses via crack closure. It has been demonstrated that in aluminum alloys the modulation is mainly due to the second effect, therefore it can be exploited for discriminating fatigue cracks against other artifacts which are much less affected by thermal stresses [9]. Measurements were carried out on a series of specimens to establish the threshold sensitivity of the thermo-optical modulation technique in aluminum at 2.25 MHz. Fig. 3a shows the measured flaw signal amplitude in an intact reference specimen and six fatigue-damaged specimens. The Al-2024 specimens were fatigued at a maximum load of 28.6 ksi, load ratio of 0.9, and frequency of 29 Hz. For each specimen we also indicated the effective fatigue crack size, which was calculated by subtracting the length of the edm starter notch (0.43 mm) from the total length of the fatigue crack on the surface as measured by optical microscopy. Generally, the higher the number of fatigue cycles, the higher the effective fatigue crack size and the detected flaw signal amplitude, although the relationship is somewhat random. Slightly better correlation can be observed between the actual crack size and the amplitude of the scattered flaw signal. The most important conclusion one can draw from these results is that the smallest 0.2-mm-long fatigue crack does not perceptibly increase the flaw signal compared to the 0.43-mm-long edm notch and would certainly remain undetected by conventional ultrasonic inspection.

Fig. 3b shows the measured modulation amplitude in the same specimens. Owing to the selective sensitivity of the thermo-optical crack-closure technique to partially closed fatigue cracks, even the smallest fatigue crack can be easily distinguished from the intact edm notch since it produces one order of magnitude larger modulation. As one would expect, after going through a maximum, the modulation amplitude actually decreases for very large cracks since the relatively weak thermal stresses produced by laser irradiation are not sufficient to close

Fig. 3. The measured flaw signal (a) and modulation (b) amplitudes in a reference specimen containing an intact edm starter notch only (darker first column) and six fatigue-damaged Al-2024 specimens at 2.25 MHz.
large, widely open cracks. This is acceptable since our main goal is to improve the detection threshold of ultrasonic inspection so that very small fatigue cracks could be detected shortly after crack nucleation. Larger cracks well above the detection threshold level of conventional inspection techniques can be readily found based on the amplitude of the flaw signal alone.

4. Quasi-static thermo-optical modulation in Ti–6Al–4V

In order to study the thermo-optical modulation in Ti–6Al–4V alloy we prepared a total of 16 specimens. Eight of them (‘‘c1’’ through ‘‘c8’’) contained starter notches and fatigue cracks between 0.5 and 1 mm in length. The other eight (‘‘n1’’ through ‘‘n8’’) contained only intact starter notches. In the following experimental results, unless otherwise indicated, the center frequency of the Rayleigh wave transducer is 5 MHz, the total time delay between the laser pulse and the arrival of the surface wave at the notch is 130\textmu s, and the repetition rate of the ultrasonic pulser is 100 Hz (twice the repetition rate of the laser).

In theory, the dynamic thermo-optical technique should provide increased sensitivity over conventional ultrasonic flaw detection in titanium alloys just as well as in aluminum. The actual sensitivity of the technique however depends on a great variety of material parameters. Due to its low thermal conductivity, the thermal diffusivity is approximately one order of magnitude lower in Ti–6Al–4V than in Al-2024, which increases the optically induced temperature gradients since the absorbed heat cannot spread out in the short time of illumination in titanium as it does in aluminum. Other parameters, however, favor aluminum. For example, the thermal expansion coefficient is higher and the stiffness is lower in aluminum. In addition to these significant differences in mechanical and thermal properties between aluminum and titanium, there is a substantial difference in optical absorption. In the near infrared region, where the Nd:YAG pulsed laser operates (≈1.06 \textmu m), the absorption in titanium is as much as 50% versus the meager 5% in aluminum, i.e., the same irradiating power produces one order of magnitude stronger heating in titanium specimens.

Fig. 4 shows the temperature and normal stress distributions in a plane normal to the surface produced by a 4-mm-diameter Gaussian laser beam in titanium at two different delays after the incidence of a 150-\textmu s-long infrared laser pulse of 300 mJ total energy. The surface region is in compression (light area with negative normal stress), while below the surface there is a region of somewhat weaker tension (dark area with positive normal stress). Depending on the depth of the fatigue crack tip, the crack can simply close, open, or initially open and later close.

Since the modulation does not entirely disappear by the beginning of the next laser pulse, a very significant cumulative effect occurs in titanium, which was not present in aluminum. Fig. 5 shows a typical thermo-optical modulation pattern observed in titanium. The laser is turned on for approximately 8 s and then the specimen is left to cool for as long as 2 min to eliminate all thermal stresses. The repetition frequency of the ultrasonic pulse was increased to 500 Hz in order to better resolve the details of the modulation pattern which is very complex compared to the case of aluminum where the modulation is mainly due to synchronous dynamic crack closure. The overall pattern can be separated into a slow quasi-static and a synchronous dynamic modulation [10]. However, the superposition of the two effects is highly nonlinear as indicated by the continuously changing amplitude of the dynamic modulation during laser irradiation. The complex quasi-static modulation
dominates the observed long-term behavior (Fig. 5a) and it lingers long after the termination of the laser irradiation. During laser illumination (Fig. 5b) the periodic dynamic modulation is also detectable, but it disappears immediately when the laser is turned off.

It was found that on the average the magnitude of the dynamic thermo-optical modulation in titanium specimens is 2.5 times larger from fatigue-damaged edm notches than from intact ones. However, there is a large scatter in the modulation data, therefore the dynamic modulation itself cannot be used to positively distinguish fatigue cracks from artifact signals as it could be done in aluminum. The main reason for this is the relatively large modulation exhibited by intact specimens. The thermo-elastic deformation itself is clearly insufficient to produce closure in 75-μm-wide edm notches, therefore the observed modulation must be directly related to the temperature variation in the specimen. The heated low-velocity spot acts like a lens bending and focusing the transmitted surface wave thereby slightly changing the reflected echo from the scatterer [11]. We used the reflection from a straight normal corner, which is obviously not affected by thermal stresses, to assess the spurious modulation caused by direct temperature variations. When the ultrasonic path between the surface wave transducer and the corner was scanned over in the lateral direction by our laser, we observed as much as 0.3 dB loss in the reflected amplitude.

The overall thermo-optical modulation in titanium is partly due to direct temperature modulation and partly due to thermal stresses. Only the latter can be exploited for enhanced fatigue crack detection, therefore we have to consider possible differences between the two contributions so that they can be distinguished from each other. Such differences include variations in spatial distribution and time dependence. First, we studied the effect of the relative position of the heated spot with respect to the damage site. It is expected that, when the damaged area is scanned by the pulsed laser beam in the axial direction, the direct temperature effect is asymmetric with respect to the scatterer; it occurs only when the irradiated spot is between the transducer and the scatterer, but not when it is on the other side of the scatterer. In comparison, the thermal stress induced modulation of partially closed fatigue cracks is expected to be symmetric to the scatterer since the resulting closure is essentially the same regardless whether the thermal expansion occurs on one side of the scatterer or on the other. There is also a substantial difference between the direct temperature and thermal stress effects when the scatterer is scanned over in the lateral direction, i.e., normal to the sound propagation and parallel to the potential crack. In most cases the direct temperature effect is expected to exhibit odd symmetry with respect to the scatterer since bending the wave in opposite directions usually produces opposite changes in the echo amplitude, unless the beam is perfectly aligned, in which case there is a symmetric, but very small modulation [11]. In comparison, the thermal stress induced modulation of partially closed fatigue cracks exhibits even symmetry with respect to the scatterer since the resulting closure is essentially the same regardless whether the thermal expansion occurs at one end of the crack or at the other.

These expectations were qualitatively verified by our experimental results. Fig. 6 shows the typical time dependence of the observed thermo-optical modulation from a fatigue crack (a) and an intact edm notch (b) at 13 different axial positions. For simplicity, only the low-frequency quasi-static modulation is shown while the high-frequency dynamic modulation was suppressed by low-pass filtering. The measurements were made at 5 MHz in 1.25-mm-steps over a scanning range of ±7.5 mm relative to the position of the scatterer. In each case the center waveform recorded directly above the scatterer is shown in thicker line for convenience. It is clear that the substantially stronger modulation observed from the fatigue crack is more-or-less symmetric to the scatterer, although it does not completely disappear when the irradiated spot is in front of the crack. On the
other hand, in the case of the intact edm notch the modulation becomes negligible when the irradiated spot is behind the scatterer, which demonstrates that the small modulation observed when the irradiated spot is in front of the scatterer, i.e., in the line of the interrogating surface wave, is entirely due to the direct temperature effect.

Fig. 7 shows the typical time dependence of the observed thermo-optical modulation from a fatigue crack (a) and an intact edm notch (b) at 13 different lateral positions. The modulation observed from fatigue cracks is not only substantially stronger than the modulation exhibited by undamaged edm notches, but it also reveals different symmetry with respect to the scatterer’s position. In the case of fatigue cracks the modulation is mainly due to thermal stresses therefore it possesses even symmetry as both ends of the crack exhibit roughly the same closure behavior. In contrast, the modulation produced by an intact edm notch is mainly due to the direct temperature effect therefore it exhibits dominantly odd symmetry. This is because in cases when perceptible modulation occurs the alignment between the scatterer and the interrogating beam is less than perfect consequently bending of the beam in opposite directions results in opposite changes in the scattered amplitude.

Figs. 6 and 7 suggest that the symmetry of the observed thermo-optical modulation with respect to the position of the scatterer is strongly dependent on whether the modulation is caused by thermal stresses via crack closure or directly by the temperature variation via the inherent temperature dependence of the intact material. However, discrimination between small fatigue cracks and other artifacts based on this difference is rendered extremely cumbersome by the need to scan the area by the laser beam after a suspected area has been identified. A simpler approach can be based on the also significant differences between the temporal modulations caused by crack closure and direct temperature variations. Beside the difference in magnitude, the most obvious difference between the measured modulation from fatigue cracks and intact edm notches is the much slower decay of the modulation from fatigue cracks after terminating the laser irradiation [10]. The most probable reason for this is that the direct temperature effect is a highly localized phenomenon which promptly disappears as the dissipated heat diffuses from the shallow surface layer into the interior of the specimen. In comparison, the thermal stress effect is more of a long-range phenomenon that lingers on as the dissipated heat becomes distributed over a larger depth.
order to demonstrate the sensitivity of this technique for fatigue crack identification, Fig. 8 shows the measured echo amplitudes and quasi-static thermo-optical modulation from eight fatigue cracks and eight intact edm notches at the center of the irradiated spot 2 s after the end of a 10-s-long laser pulse at 5 MHz. The weakest modulation from a fatigue crack (c7) is approximately 13 times larger than the strongest modulation from an intact edm notch (n2). Clearly, no reliable detection can be achieved based on the amplitude of the ultrasonic scattering itself, while the thermo-optical modulation uniquely identifies all of the otherwise hidden fatigue cracks.

5. Conclusions

We have investigated the feasibility of unequivocal discrimination of real fatigue cracks from spurious artifact signals produced by other scattering objects. The suggested method is based on the susceptibility of partially closed fatigue cracks to parametric modulation by normal stresses. 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 often 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 irradiation 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. The resulting transient thermo-elastic deformation perceptibly changes the opening of partially closed surface cracks without affecting other scatterers, such as surface grooves, corrosion pits, coarse grains, etc., that might hide the fatigue crack from ultrasonic detection.

The dynamic thermo-optical modulation method has been shown to be capable of identifying small fatigue cracks in aluminum alloys, where the high-thermal diffusivity of the material results in a strong synchronous modulation. Unfortunately, the same technique was found to be much less effective in titanium alloys because of their much lower thermal diffusivity. The high-temperature coefficient of the sound velocity in titanium further complicated the problem by introducing a direct temperature modulation even in the case of scatterers that would not exhibit stress induced crack closure at all. This spurious modulation is caused by direct thermal modulation of the sound velocity in the material rather than thermal stresses via crack closure. These difficulties prompted us to modify the thermo-optical method and rely on the slow quasi-static modulation for fatigue crack detection instead of the previously used fast dynamic modulation. With this modification we have successfully demonstrated the feasibility of thermo-optical fatigue crack identification in Ti–6Al–4V. We found that the suggested thermo-optical modulation method can increase the detectability of hidden fatigue cracks in Ti–6Al–4V specimens by approximately one order of magnitude.

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