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Laser Ultrasonic Imaging of Structural Microcracks

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Abstract
Lasers provide a non-contact and remote inspection method with high resolution and sensitivity. As a crack detection tool, laser ultrasonics can be used to image surface-breaking cracks with microscopic precision. By monitoring the local elastic scattering conditions and dynamic motion fields present in the immediate vicinity of a surface-breaking crack site, the local crack morphology can be mapped out in significant detail. Several crack imaging examples are provided for imaging and characterizing microscopic, surface-breaking cracks in aerospace superalloys. Brief overviews of laser probe methods, displacement-field imaging, and crack imaging are discussed.
Keywords: Nondestructive Evaluation, Laser Ultrasound, Surface-Breaking Cracks

1. Introduction

Crack measurements using ultrasonic inspection methods have a long history, and are currently one of the most widely used for the nondestructive examination of engineering materials and structures. This is primarily due to the advantages of simplicity, low cost, high signal-to-noise ratio, and good detection sensitivity. Because the ultrasonic energy is intimately coupled to the underlying material substrate, measurements of ultrasonic attenuation, phase velocity, reflectance, and frequency provide a wealth of information regarding the state of the material being evaluated.

Current ultrasound inspection methods provide a capability for detecting surface-breaking cracks with sensitivity levels approaching 100 microns in crack length, and 10 microns in crack depth. Traditional ultrasound methods are, however, often limited with respect to the amount of *quantitative* information they can provide for realistic cracks. To a large degree this is due to the complex nature of elastic wave scattering processes from the microscopic features and surfaces of a typical crack. Depending on the ultrasonic wavelength used, and the physical characteristics of the crack, the scattering may take on many different forms which can include: reflection, diffraction, scattering, mode conversion, and transmission of the elastic wave energy. All of these processes tend to complicate the crack sensing signatures and signals for an ultrasound measurement, which are also limited to the far-field with respect to the ultrasound wavelength used.

With the development of laser technologies in the 1960’s and 1970’s, and the subsequent use of lasers for generating and detecting ultrasound in the 1980’s and 1990’s [1], the ability to probe cracks and other defects in the ‘near-field’ became possible [2]. This is due primarily to two useful characteristics of laser beams including the ability to probe a material surface with microscopic resolution levels, and the ability to probe the material surface in a non-interfering manner. Both of these aspects of laser ultrasound provide a unique capability for probing and understanding elastic wave scattering processes in the near-field of a surface-breaking crack.

In this research effort, a technique termed ‘Displacement-Field Imaging (DFI)’ is described, which provides a means for studying the dynamic and time-averaged displacement characteristics of elastic waves on a material surface. As a practical tool, the DFI technique can be used to nondestructively characterize the detailed, microscopic features of a surface-breaking cracks.

2. Experiment

2.1 Displacement Field Imaging

A schematic diagram depicting the basic measurement process for acquiring a Displacement-Field Image is provided in Figure 1. A traditional ultrasonic transducer generates surface acoustic waves (SAW) on the material surface, and a laser beam probes the SAW displacements as it propagates along the material surface. The laser system probes the material surface at normal incidence with a focused laser beam, and receives the reflected/scattered light along the same path as the incident light. Through a well-understood optical heterodyne, light interference process [1-3], the surface motions are converted into phase differences in the laser beam, which are subsequently converted into an electrical voltage signals that precisely follow the out-of-plane displacement levels occurring on the material surface. By raster scanning the position of the beam, different locations can be probed, and a complete displacement-field image can be built up of an area on the material surface (typically mm^2 to cm^2).

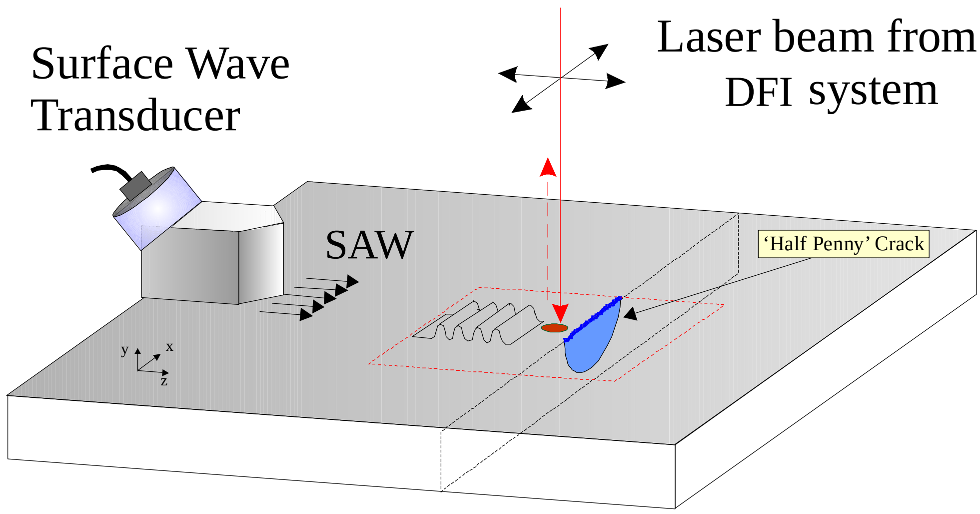


Figure 1. Schematic diagram depicting measurement process for Displacement-Field Imaging method.

In its most basic form, therefore, the Displacement Field Imaging (DFI) approach provides an advanced nondestructive evaluation (NDE) capability for ‘imaging’ ultrasonic fields on a material surface. This permits detailed measurements of ultrasonic field parameters related to ultrasonic wave dispersion, phase velocity, attenuation, and localized scattering to be made with high sensitivity and resolution. Each of these ultrasonic wave parameters, in turn, can be used to assess the underlying material structure with microscopic precision. The DFI system is capable of tracking the instantaneous out-of-plane motions occurring on a material surface, and because of this, a variety of measurement options are available for the system. The use of a narrow time-gate detection scheme, for example, provides a means for resolving the instantaneous features of a propagating ultrasonic wave, while the use of a wide time-gate detection scheme, provides a measure of the time-averaged, peak-displacement levels of an ultrasonic wave. These two basic time-gated detection schemes constitute the primary operation modes for the DFI method, and Figure 2 provides measurement examples using each detection scheme for a single-pulse SAW.

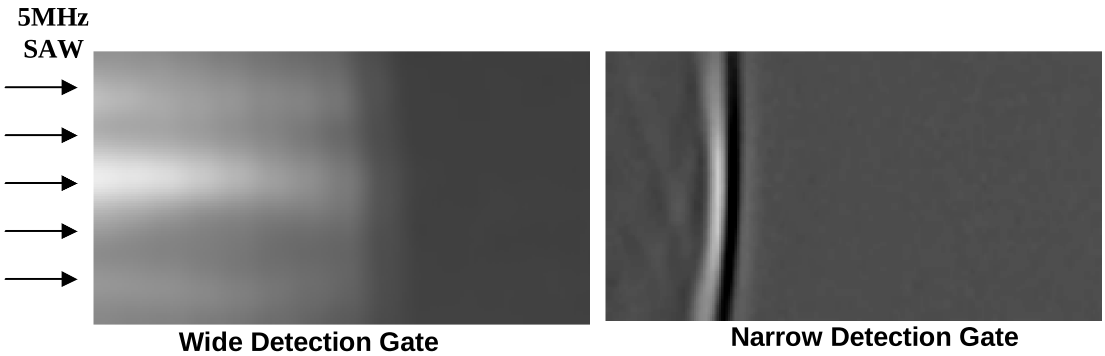


Figure 2. Examples of time-averaged (Left) and instantaneous (Right) displacement-field images taken with wide-gate and narrow-gate detection, respectively.

As shown in the wide detection gate image in Figure 2, the use of a wide time-gate provides an image of the *general structure* of the ultrasonic wave as it sweeps across the material surface. The DFI system determines the peak displacement level within the entire time-gate window, and outputs a single ‘peak’ value as its measurement for an individual point on the material surface. As shown in the wide-gate schematic diagram in Figure 2a, the ultrasonic wave does not change considerably as it propagates past individual measurement points. The displacement-field image generated using a wide time-gate, therefore, represents a ‘time-averaged’ displacement field measurement of the maximum out-of-plane displacement of the ultrasonic field at each spatial point.

The use of a narrow time-gate detection scheme, in contrast, provides a means for discriminating the phase of an ultrasonic waveform as it sweeps by individual measurement points on the material surface. When raster-scanned in a point-by-point manner, the DFI system samples and measures this relative phase information point-by-point, resulting in an instantaneous image of the ultrasonic wave ‘frozen’ at a single instant in time. The image is frozen at a time determined by the narrow time-gate delay (i.e. the start of the time-gate detection window). An example of this is provided in Figure 2, where a narrow time-gate of 10 ns has been used to sample and image the instantaneous wavefront features of a 5MHz surface acoustic wave (SAW) impulse. The sinusoidal nature of the SAW is easily seen in the image, and accurately follows and represents the instantaneous displacement level of the SAW at a time-delay of 10.5 microseconds after the triggering of the transducer drive system

2.2 Surface-Breaking Crack Imaging

Surface-breaking fatigue cracks are typically small in lateral extent, scattering and diffracting only a very small fraction of the incident ultrasonic energy, which make them difficult to detect. In addition, they tend to be shallow with minimal cross-sectional area, which means they reflect only a small fraction of the incident SAW energy. In the far-field, therefore, it is very difficult to detect microscopic fatigue cracks using traditional NDE approaches. However, in the near-field, scattering process involve an additional local intensification of the ultrasonic energy [2,3], which can be imaged directly using the DFI technique. Even very small cracks that reflect and scatter very small amounts of energy can still be imaged effectively.

Figure 3 provides a measurement example of a small microscopic fatigue crack in a titanium material substrate obtained using the DFI technique. The crack was located in the center portion of the sample and was ~250 μm long and very shallow (~25-40 μm deep). As shown in Figure 3a, the crack is not immediately observable by visual inspection, even at 100x optical magnification levels. As shown in Figures 3b and 3c, however, the crack was successfully imaged as a small, localized displacement-field intensity increase superimposed on the main ultrasonic SAW field. The 5MHz SAW in this case was incident from the top of the page propagating downward

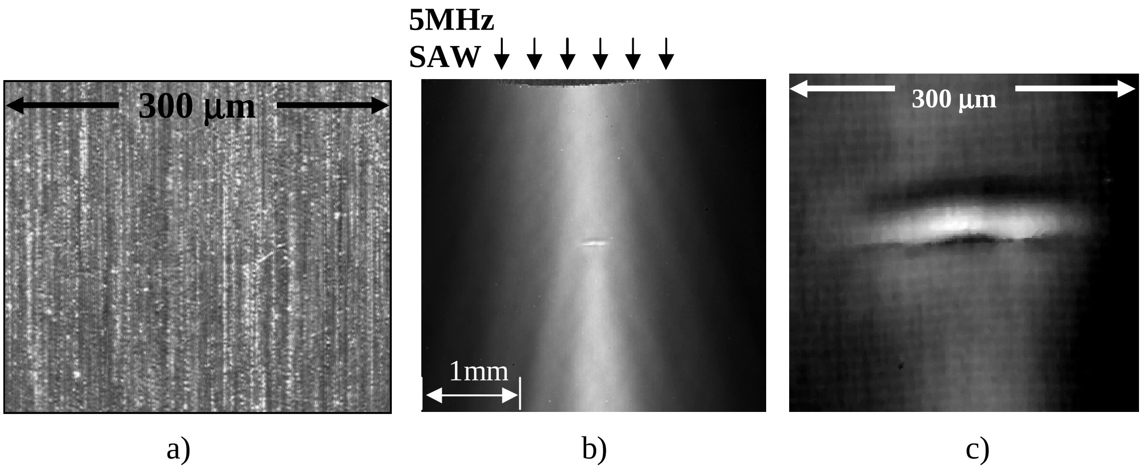
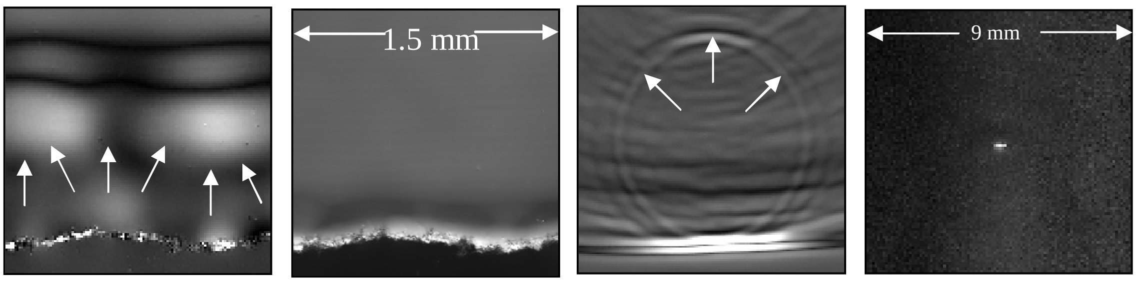


Figure 3. a) Digital image of titanium surface with surface-breaking crack at 100x magnification, b) displacement-field image of crack, and c) detailed DFI scan image of crack region.

In order to highlight the advantages of the DFI measurement approach relative to traditional NDE approaches, a series of measurements were made using the DFI technique to image the near-field and far-field ultrasonic waves being reflected/scattered from realistic and complicated cracks. The results of this study are presented in Figure 4, where a comparison of narrow time-gate (Figures 4a and 4c) and wide time-gate (Figures 4b and 4d) images are presented. As described in the previous section, the narrow time-gate approach provides a capability for imaging the interaction of SAW with complicated cracks at a frozen instant in time, while the wide time-gate approach provides a 'time-averaged' image of the crack-SAW interaction. The SAW was propagated from the top of each figure towards the bottom, and resulted in very complicated reflected/scattered waves that propagated primarily from the bottom-up in each figure. In a traditional ultrasonic NDE measurement, a piezoelectric receiver transducer would acquire a complicated displacement-vs-time signal in the far-field as a result of these scattered/reflected waves. As shown in the figure, this signal would be made of the various waves as they propagate, reflect, scatter, diffract, and attenuate. The detection and characterization of these cracks would be clearly difficult using traditional ultrasonic NDE.



a) b) c) d)

Figure 4. Displacement-field images based on: far-field scattering effects a) and c); and near-field scattering effects b) and d), for two different crack types.

The images in Figures 4b and 4d were generated using the same crack and SAW conditions used in Figures 4a and 4c, however, a wide time-gate detection approach was used to highlight the near-field intensification of the SAW in the immediate vicinity of the cracks. This resulted in a measure of the time-averaged, peak-displacement levels in each image which created a dramatic visualization of the crack positions and their detailed structures.

3. Conclusions

By monitoring the local elastic scattering conditions and dynamic motion fields present in the immediate vicinity of a surface-breaking crack site, the local crack morphology can be mapped out in significant detail using a technique termed ‘Displacement-Field Imaging’. In effect, the time-averaged, peak displacement levels are mapped out by a laser scanning beam using heterodyne interferometric principles. As a practical tool, the DFI technique was shown to be capable of nondestructively characterize the detailed, microscopic features of several surface-breaking cracks.

References

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