Ultrasonic Birefringence Measurements of Elastic Anisotropy in Fatigue Damaged Brass, Copper and Aluminum Alloys

Lindsey R. Lindamood and James B. Spicer
Department of Materials Science and Engineering
Johns Hopkins University
channels@jhu.edu

Abstract

Texture produced by sheet rolling operations results in elastic anisotropy that can be measured using ultrasonic, shear wave birefringence measurements. Preferred grain orientation produces elastic modulus variations that affect ultrasonic modes propagating in various directions relative to the rolling direction. Variations in ultrasonic wave polarization relative to the rolling direction can also affect wavespeed. By fixing the propagation direction and altering wave polarization, birefringence measurements can be made. Aligned microcracking is also known to produce elastic anisotropy in materials. If these types of fields are produced during controlled fatigue loading, then shear wave birefringence techniques might be used to assess fatigue damage. Texture models indicate that shear modulus will change as a function of angle relative to the rolling direction and can be directly converted to wavespeed, such that in brass we expect a greater than 4% change in shear wavespeed as a function of polarization angle. In this work, we present shear wave birefringence measurement results on unfatigued and fatigue damaged materials assessing modulus and anisotropy variations. For these measurements, a laser line source has been used to generate longitudinal and shear waves that are detected in the through-thickness direction of rolled plate material using a Michelson-type path-stabilized interferometer allowing for high-fidelity recording of ultrasonic arrivals. The line source controls generation of particular shear polarization states in the ultrasonic pulse. We will present results for as-received and fatigued rolled sheets of brass, copper, and an aluminum alloy (2024-T351).

Key words: fatigue, ultrasound, birefringence

Introduction

Structural health monitoring and prognosis rely on diagnostic systems assessing damage accumulation in a material. Permanent ultrasonic contacting sensors are often used as one of these diagnostic systems and can provide limited information about the state of the material for an estimation of the structure’s remaining lifetime. This type of system cannot isolate local damage, but it can alert the user to significant damage accumulation somewhere in the material. Early detection of material damage is critical when monitoring aircraft, bridges, and other infrastructure, and it is often very desirable that the detection be nondestructive, such that the incipient damage can be detected while keeping these structures intact and protected from further damage. The United States’ Federal Aviation Administration1 has reported on the inability to
detect widespread fatigue damage (WFD) as well as the fortuitous discoveries of WFD in numerous in-commission aircraft often during routine cosmetic maintenance or by mechanics. Some cracks discovered prior to flight have been on the order of two feet long, and if these aircraft were to take flight the result could have been severe. Ultrasonic techniques can be used to measure properties such as attenuation, wavespeed, and changes in the transmitted frequencies affected by microstructural changes that initiate material failure. The subject of our research is motivated by the need to identify damage in aircraft materials before catastrophic failure. Specifically, we aim to detect fatigue damage prior to crack formation by monitoring changes in material elasticity, thus providing a way to localize material damage for structural health monitoring applications.

**Background**

Ultrasound interactions with the microstructure of a material provide the basis for powerful yet nondestructive methods to monitor changes in material mechanical properties. Ultrasonic waves can be transmitted using a variety of techniques including contacting transducers, electromagnetic acoustic transducers and lasers. We will combine the theory of texture measurements developed from other ultrasonic work with a modified laser ultrasonic technique to measure shear wave birefringence. Various techniques can be used to measure the texture of a material, ultrasound being one alternative that has been implemented by many authors.\(^2,4-6,10\)

Shear waves, propagating at various angles relative to the rolling direction, have been measured in metal alloy strips to extract texture information using the maxima and minima velocities at 0, 45, and 90 degrees between the propagation and rolling directions (rolled plates have orthorhombic symmetry while extruded bars and wires are transversely isotropic).\(^2,3\) Texture has also been measured using the Young’s modulus of various materials as a function of angle relative to the rolling direction. Even in highly isotropic materials like aluminum and tungsten this method could still be applicable since Young’s modulus can be accurately measured to 1 part in 10\(^4\) which is beyond the ability to produce elastically isotropic, polycrystalline materials.\(^3\) Extruded aluminum was found to have a maximum velocity when the wave propagated 45 degrees from the extrusion direction and a minimum when the wave propagated parallel to this direction.\(^4\) Textures in copper and in copper alloys containing zinc were measured with ultrasound and compared to neutron diffraction measurements of the orientation distribution coefficients.\(^5\) Results did not reveal significant anisotropic behavior in pure copper, but the addition of zinc produces significant texture that can be easily characterized using ultrasound. By generating Rayleigh and bulk waves in various aluminum alloys, small changes in velocity have been observed and the stress required to cause the initial anisotropy has been calculated.\(^6\) Ignoring this anisotropy significantly affects the accuracy of the stress calculation.

**Point source laser ultrasonic interactions with fatigue damaged materials**

Previously, results on fatigue tests of the aluminum alloy 2024-T351 indicated that changes in material’s elastic properties can be measured using ultrasonics.\(^7\) The data shown in Fig. 1 were generated using a focused laser source to transmit ultrasound and a conical contacting transducer for detection (0.5 – 1.5 MHz). The source and receiver were located on epicenter to measure the shortest longitudinal wave arrival time. Before the test coupons fail or surface cracking becomes visible, a decrease in shear wave time-of-flight is observed (Fig.1a). Indications of a possible
birefringence effect seem to be revealed in the shear arrival of some fatigue damaged materials. Figure 1b shows ultrasonic data from the same fatigued aluminum specimen at the end of its lifetime with collection occurring in the most fatigued region. The distortion in the waveform at the minima arrival could be an indication of ultrasonic interaction with fatigue damage and the birefringence effect. There are experimental techniques that can be considered for proof of the birefringence observations. These results gathered with a point laser source have guided experimental investigations focused on measuring material anisotropy and how changes in the microstructure due to fatigue damage affect material isotropy.

Figure 1: a. Ultrasonic waveforms for aluminum at different stages in fatigue lifetime, 0 to 80 kilocycles. A shift in the first minimum (corresponding to the shear wave arrival) is noted towards the end of life at 80 kilocycles. b. Four waveforms from the damaged region at 80 kilocycles in one of the fatigued samples shown in 1a. A distortion in the shear wave arrival (at 2.0µs) occurs indicating shear-specific interactions with microstructure. 7
Toward this end, in this work, a laser line source has been used to generate longitudinal and shear waves simultaneously in the through-thickness direction of rolled plate materials. The line source enables us to isolate shear wave polarization that can be varied by rotating the line. Microscopic changes to materials that occur during fatigue processes should result in texture variations that might influence the ultrasonic properties. This paper will show experimental results of changes in wavespeed relative to the rolling direction in as-received materials using the laser-line ultrasonic technique to establish pre-fatigue baseline characteristics. These results will be used to explain how grain orientation affects ultrasonic wave propagation. Changing the propagation direction of the ultrasound to measure elastic properties of materials is a more commonly used technique. The work described here will focus on changing the polarization direction and maintaining the propagation direction. This method does not affect longitudinal wave propagation since neither the propagation direction nor the polarization of that wave are changed in our experiments.

This type of polarization control is analogous to earlier studies that used polarized electromagnetic acoustic transducers (EMATS) to assess shear birefringence using through-thickness resonance measurements. We have performed data analysis in the time-domain since the laser ultrasonic system bandwidth allows for the measurement of very small changes in shear wave times-of-flight that result when the line is rotated relative to rolling direction in plate samples. In general, materials can sustain one longitudinal wave polarized in the propagation direction and two orthogonally polarized shear waves. In a rolled material these shear waves each have a favored velocity when polarized either in the rolling direction or in the transverse direction. By polarizing the ultrasonic source we can isolate each shear wave, and measure the change in velocity as a function of ultrasonic polarization. Normally when the ultrasound propagates through a highly isotropic medium, such as an aluminum alloy, only one shear wave arrives. However, for a rolled plate of material, including aluminum, either both shear waves are detected, or changes in wavespeed are observed as source polarization changes, without changing propagation direction. At various orientations (usually around 45 degrees from the rolling direction) both shear wave arrivals can be isolated. These results were also seen when using a point source ultrasonic generator and receiver in a unidirectional, fiber-reinforced composite material. The source and receiver were aligned on epicenter but because of the dispersion effects of the material (such as occurs for fiber direction perpendicular to wave propagation) the fast and slow shear waves were detected.

Laser line sources for ultrasonic generation have been used by other authors to study wave propagation in the principal directions of a fiber reinforced composite plate while assuming transverse isotropy. When the laser line is perpendicular to the fiber direction (anisotropic plane), stress fields are symmetric about the isotropic plane and ultrasound propagates parallel to the anisotropic plane. When the laser is parallel to the fiber direction (isotropic plane), waves propagate parallel to the isotropic plane. In general, there are three possible modes generated by ultrasound: pure shear, quasi-shear, and quasi-longitudinal. However, with a laser line source no pure shear mode is generated when polarization is perpendicular to the fiber direction. A line source has also been used to predict the acoustic field generated in a transversely isotropic cylinder.
Line source experiment and results

Materials used in these experiments include as-received rolled square plates measuring 5cm x 5cm x 0.476cm in alpha brass Cu64Zn36, and copper, as well as 5cm x 5cm x 0.635cm aluminum 2024-T351. Specimens were also cut from extruded round bars of brass, Al6061 and Al2024. The addition of copper and brass to the sample set is useful in establishing a range of detectable anisotropy based on material composition, and increasing the amount of zinc in brass is known to yield a higher anisotropic material. Each material used in this experiment has individual crystallites with cubic symmetry, but rolling gives the sample orthorhombic symmetry.

For ultrasonic wave generation, a pulsed Nd:YAG laser beam was routed through a double concave lens and a double convex lens for expansion and collimation, and then finally focused into a line with a cylindrical lens as shown in Fig. 2. The resulting line measured approximately 20mm x 0.35mm and pulse energies were adjusted to provide a low fluence for thermoelastic wave generation. Both the ultrasonic generation beam and the receiving beam were arranged to make contact with the exact center of rotation of the sample such that measurement occurred in the epicentral geometry. Data is collected at 15 degree intervals with 500 waveforms being averaged at each angle.

![Figure 2: Laser ultrasonic system with laser line generation and optical detection using a path-stabilized, Michelson-type interferometer.](image)

To specify the orientation of the laser line source, angles were measured between the rolling and shear wave polarization directions. A line oriented perpendicular to the rolling direction is at zero degrees since the polarization is along the rolling direction. When the line is parallel to the rolling direction, the angle is 90 degrees. The shear wave time-of-flight was determined using the minimum amplitude in the recorded ultrasonic waveform. In some cases both shear waves appear, but one dictated the waveform minimum and this arrival was used to record an effective time-of-flight. Times-of-flight were recorded and converted to velocity and stiffness using measurements of the sample thickness and values for material density.
Figures 3 and 4 show the measured results as polar plots using the angle of rotation and the velocity or stiffness calculation. Data taken in rolled aluminum plates or in samples cut parallel to the extrusion direction in bars yield two-fold symmetric plots of wavespeed versus line orientation as seen in Fig. 3a. Since polycrystalline aluminum is generally considered to be relatively isotropic compared to other cubic metals/metal alloys, these experimental results show that the small anisotropy present, approximately 1.5 percent (uncertainty +/- 0.3%), can be measured using shear wave birefringence. Stiffness results of brass are shown alongside aluminum in Fig. 3b demonstrating a more defined symmetry and smaller uncertainty in all line orientations with stiffness variations up to nine percent. Velocity data on a heat treated rolled aluminum plate specimen, shown in Fig. 4a, exhibits isotropic behavior potentially due to the successful removal of rolling-induced plastic deformation. Compare this result to that of an extruded bar of aluminum with ultrasound generated transverse to the extruded direction, shown in Fig. 4b with a 1.5 percent change in velocity (shown with an elliptical fit to exaggerate symmetrical points of interest). A decrease in velocity can be observed when the shear wave is polarized in the rolling direction (line oriented perpendicular to the rolling direction).

Figure 3: a. Aluminum 6061 extruded bar with propagation transverse to the isotropic plane  
b. Stiffness measurement using interferometric detection on 64/36
Conclusions

Successful application of laser line source for ultrasonic generation in various metal alloys has been employed as a method for detecting material anisotropy. This technique arose out of need to quantify fatigue damage prior to crack formation, and isolate initial material characteristics prior to fatigue such that small changes in elastic stiffness could be measured. Although aluminum is known to be a highly isotropic material, when it is in a cold rolled state preferred orientation of the microstructure induces enough directional anisotropy to influence variations in ultrasonic propagation.

References


