Visualisation of Acoustic Birefringence

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Abstract
Polished quartz crystal has been used to allow photoelastic visualisation of acoustic pulse splitting due to the birefringence of quartz. An incident compression mode from a phased-array probe is used to demonstrate how the refracted wave is split into slow and fast shear components. This provides useful understanding of the nature of the quasi-shear modes and what can occur in anisotropic materials such as TMCP (thermo-mechanical control process) steels.

Keywords: Photoelastic, anisotropy, birefringence, ultrasonic, shear velocity

1. Introduction

In a recent paper by the authors [1], the effects of acoustic birefringence were discussed and a method for calculating the actual refracted angles of the major energy flow described. Errors in plotting flaw locations due to acoustic birefringence have been known and reported since the 1980s [2]. Acoustic birefringence is essentially the splitting of the shear mode into slow and fast components as a result of surrounding stresses or stiffness differences in the lattice.

Birefringence has been known to exist in other applications as well. In geology, seismic analyses can identify early and later arrival shear modes. In optical minerology, birefringence of light is often used to identify minerals. This paper takes advantage of both the acoustic and optical birefringence present in quartz to provide a realistic visual presentation of the resulting wavefronts that form in a solid due to acoustic birefringence.

2. Crystal Structure

Crystals are grouped into 7 systems; triclinic, monoclinic, orthorhombic, tetragonal, hexagonal, trigonal and isometric. Most steels are considered to be simple orthorhombic (cubic) crystal structures with three mutually orthogonal planes. In all but the trigonal and hexagonal systems, simple reference systems using labels “a”, “b” and “c” are used with the axes at right angles. In spite of its characteristic six sides, quartz crystals are considered to be in the trigonal system in which the reference axes are labelled a_1, a_2, a_3, and c (Figure 1).

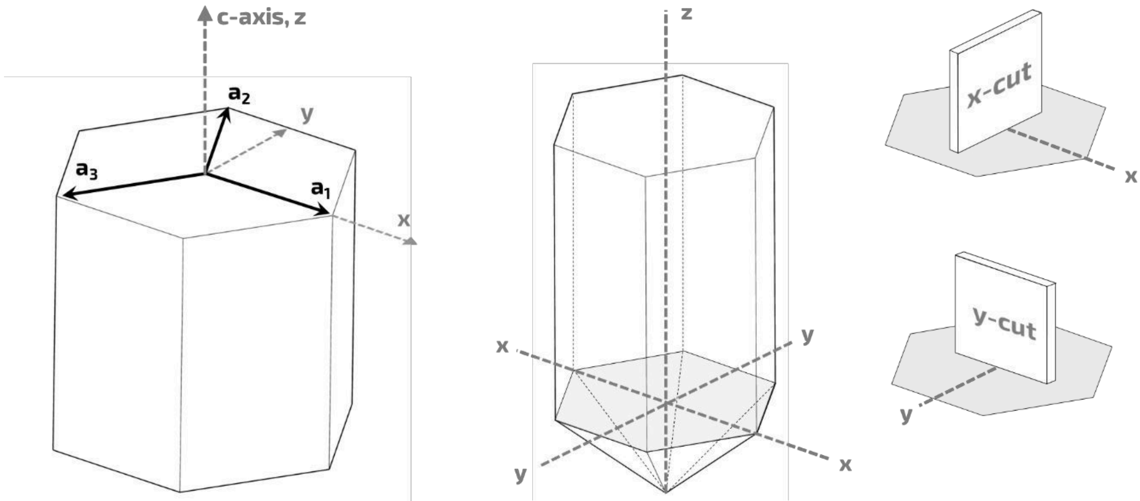

Figure 1: Quartz reference axes

Identification of axes can get complicated. There are axes based on the lattice planes (crystal axes); there is the optic axis which is the direction in which a ray of light experiences no birefringence; and for quartz we have used piezo-axes to define the type/direction of vibration based on the plane that the crystal has been cut.

Quartz has long been known for its piezoelectric properties and was one of the first materials used to manufacture ultrasonic transducers. In order to generate the compression mode using a quartz crystal it was cut perpendicular to the X-axis. Optically, quartz is considered to be uniaxial meaning there is only one axis along which birefringence does not occur.

The a_1 axis in quartz aligns with the X-axis associated with the piezoelectric function. The Y-axis is perpendicular to the faces of the prismatic portion of the crystal. One such axis is therefore perpendicular to the X-axis. The crystallographic reference axis identified as "c" is considered the Z-axis when used in the piezo-electric coordinate system. The Z- or c-axis is also the optic axis in quartz.

3. Experimental Setup

In preparation for the experiment, a large quartz crystal was ordered from an optical component supplier, OptoCity in North Carolina, USA. The crystal measured 77mm square with a 25mm thickness in the Z-direction and was polished on all six surfaces. One surface was cut perpendicular to the X -direction and since one of the Y piezo-directions is perpendicular to the X-direction, it results in the other surface cutting perpendicular to a Y-axis (Figure 2).

Using a 5MHz mono-element compression mode and a 5MHz normal incidence shear mode (SH) probe, acoustic velocities in the three mutually perpendicular directions were determined. These velocities are tabulated in Table 1. Not only is the Z-axis the optic axis (in which light birefringence does not occur), it is also the axis along which no acoustic birefringence occurs. In the table, P-mode indicates the compression mode velocity, S1 is the faster of the shear modes and S2 the slower of the shear modes. S1 and S2 are also sometimes called the quasi-transverse fast and slow waves (QT1 and QT2). The table indicates a Y-direction which is the direction at right angles to the X-direction or a_1 direction.

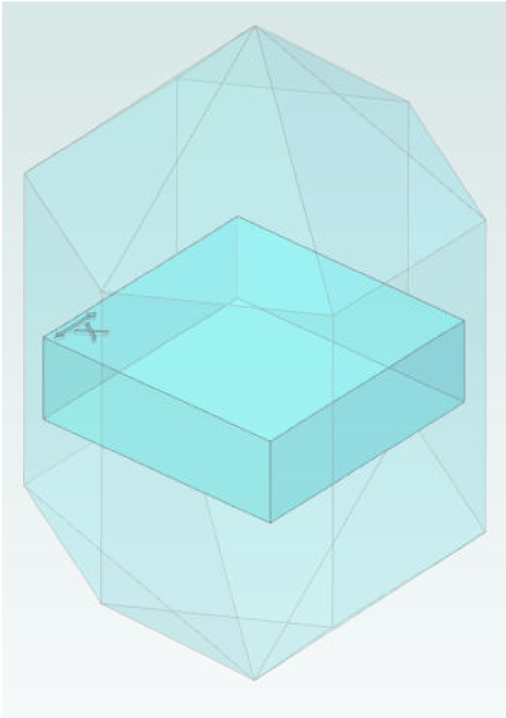

Figure 2: Orientation of sample prior to being cut from synthetic crystal

Table 1: Acoustic Velocities in Quartz Crystal Sample

Direction	P-mode (m/s)	S1 (m/s)	S2 (m/s)
Z [001]*	6308	4530	N/A
X [100]	5687	5105	3360
Y [010]	5168	3633	3250

*Note: the square brackets [ ] denote "direction" in Miller Indices

Having determined the acoustic velocities in the directions normal to the faces, a phased-array probe was configured with a null delay law (no steering) that would generate an incident beam at the wedge angle of 17°. The wedge material had an acoustic velocity of 2340m/s and the probe was driven with an applied voltage of 200V (negative square wave).

First, the probe was coupled to the 25mm surface with the beam in the direction perpendicular to the Z-axis. Figure 3 illustrates the probe placement and an outline of a hexagonal shape indicates how the sample was cut. The X-direction was determined based on the acoustic velocities. The X, the arrow, and the hexagonal outline on the image were not permanently identified but are included in the image to indicate the direction of the X-axis.

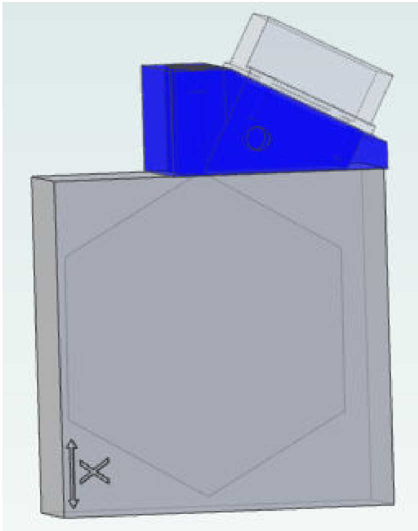

Figure 3: Probe position on quartz sample

4. Photoelastic Image Results

The test assembly was aligned in the photoelastic light beam and the polarising lenses adjusted to optimise the image of the local stress condition formed by the ultrasonic pulse in the quartz. The images were captured in a video format and then processed to allow adequate contrast for publication. Figure 4 illustrates two positions of the pulse in the quartz.

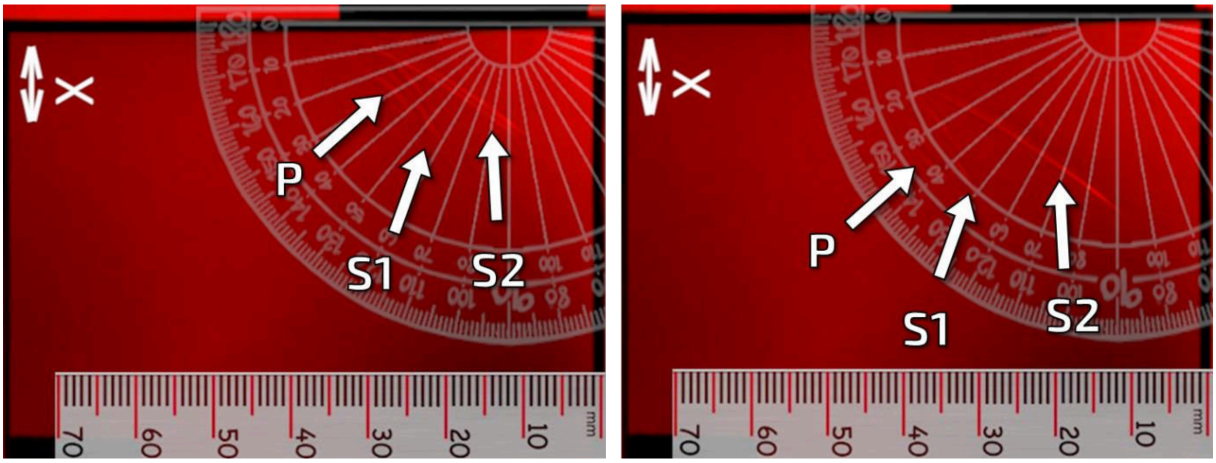

Figure 4: P, S1 and S2 pulses in quartz with probe on Y-plane

The setup was repeated with the probe placed on the surface parallel to the X-axis. When imaged in the photoelastic system, the P-mode is seen to have a smaller refracted angle and the shear pulses can be seen (Figure 5) to be separated by a slightly smaller angular difference. This indicates that the S1 and S2 components have acoustic velocities that are closer to the same value as compared to the image in Figure 4.

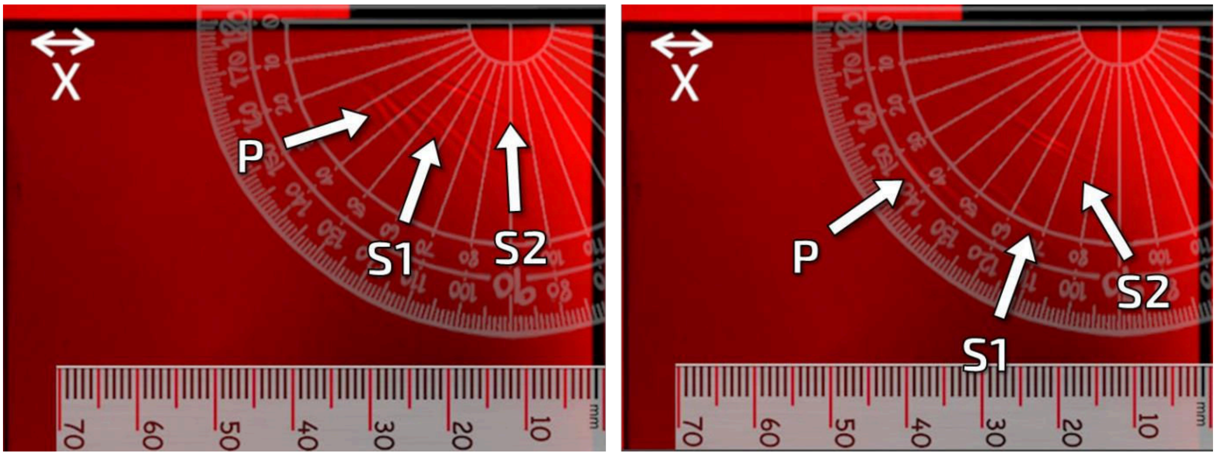

Figure 5: P, S1 and S2 pulses in quartz with probe on X-plane

5. Discussion

Quartz has been studied for well over 100 years and has well documented physical parameters. Of importance to understanding acoustic velocities are the stiffness tensors. In a relatively recent publication, Heyliger [3] has tabulated tensor values for natural quartz. Although their study was on natural quartz and the quartz sample used in this study was synthetically grown in an autoclave, the values for the natural quartz are considered to be representative of the synthetic variety. Tensor values provided by Heyliger were input in the anisotropic material matrix in Civa simulation software. The resulting rays predicted by Civa were found to be very close to those observed in the photoelastic imaging. The photoelastic ray directions are overlaid on the Civa predicted ray images in Figure 6.

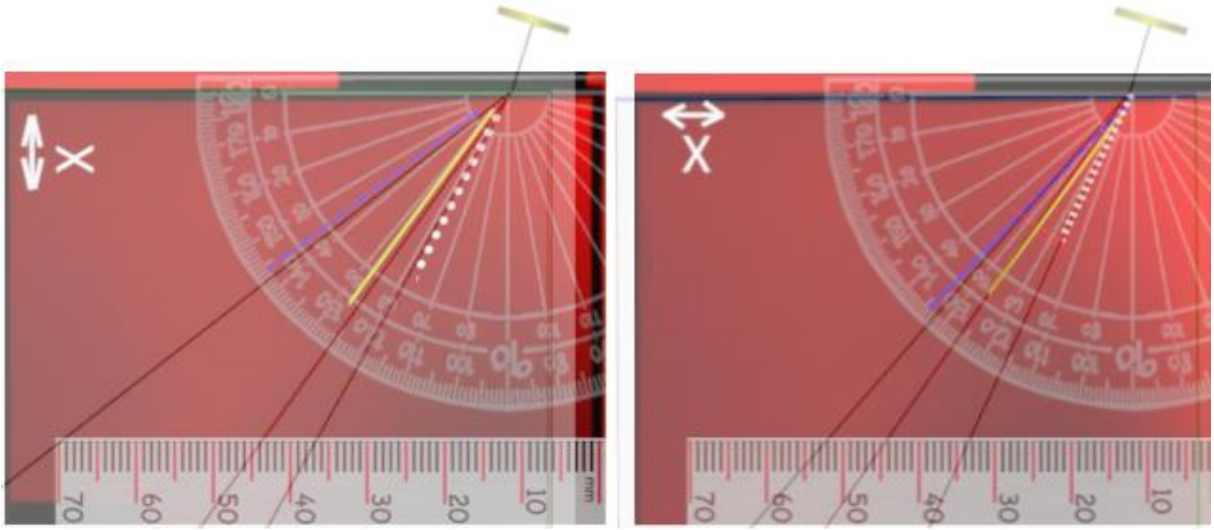

Figure 6: Civa path rays in quartz based on stiffness tensors compared to travel paths

The figures illustrate the presence of three separate pulses present in the quartz. The protractor is overlaid in the images to allow an estimate of the acoustic velocities based on the refracted angles. Velocities can be estimated using Snell's Law. Since the acoustic velocity of the wedge is known (2340m/s) and the incident angle is known to be 17°, using the protractor we can estimate the refracted angles of the P, S1 and S2 pulses. This allows us to estimate the velocities.

Using the angles seen in Figure 4 for the X-axis vertical, the angles for P, S1 and S2 are 52°, 38° and 28°. This would suggest that the velocities experienced by these pulses can be estimated as 6300m/s, 4900m/s and 3750m/s.

Using the angles seen in Figure 5 for the X-axis horizontal, the angles for P, S1 and S2 are 43°, 35° and 27°. This would suggest that the velocities experienced by these pulses can be estimated as 5450m/s, 4600m/s and 3650m/s.

Theory predicts that the S1 and S2 pulses are polarised at right angles to each other (Figure 7). To test this theory, a pitch-catch arrangement was configured using the phased-array probe as a transmitter synchronised with a mono-element SH-shear wave probe as the receiver. Separate pulser-receiver instruments were used with their functions synchronised using a common TTL trigger from the strobe-light source in the photoelastic system.

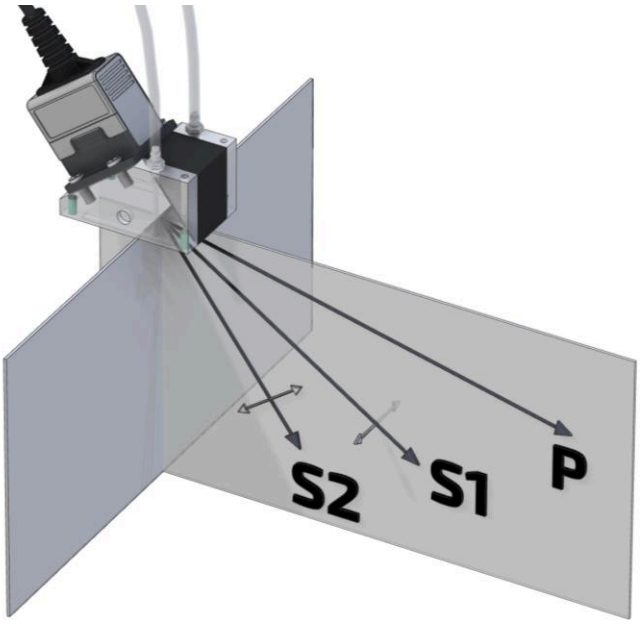

Figure 7: Perpendicular particle motion for S1 and S2 modes

The SH shear wave probe was coupled to the vertical face of the quartz and moved to the positions where the S1 and S2 pulses could be seen impinging on the photoelastic image. These positions were confirmed by observing the amplitude response as the SH shear wave probe was moved along the surface (Figure 8). Both block orientations were assessed as indicated in Figure 9.

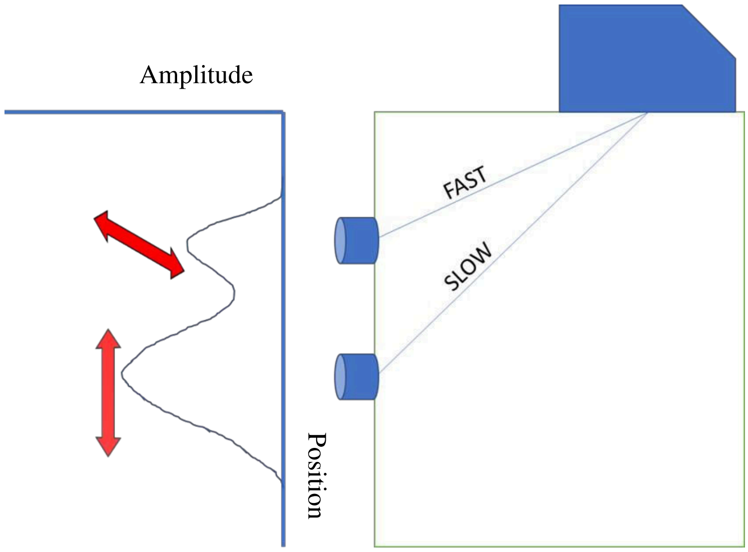

Figure 8: Locating S1 and S2 modes based on echo dynamics of SH received pulse

The faster S1 pulse refracts at a higher angle so is found at the upper area of the block's vertical face. Depending on the plane surface that the transmitting phased-array probe was positioned, orientation of the polarisation differed.

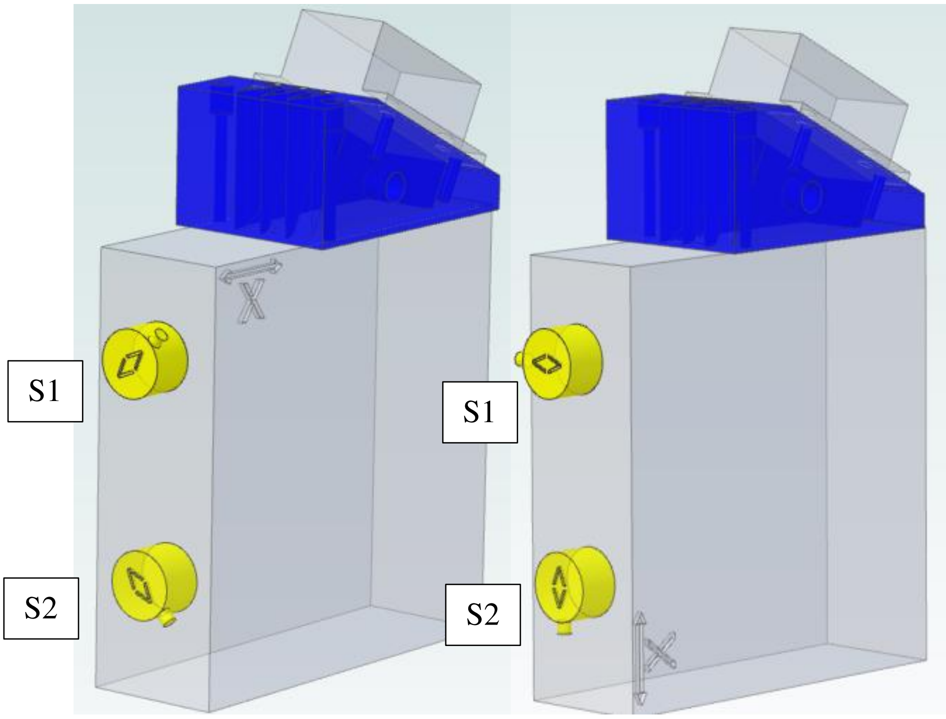

Figure 9: Positions and orientations detecting polarisation of S1 and S2 pulses in quartz

6. Conclusions

Photoelastic imaging has been used to visualise the splitting of the shear mode in a sample of acoustically birefringent quartz. The S1 and S2 quasi-transverse waves were detected using a normal incidence (SH) shear wave probe as a receiver and the preferential polarisations identified. Polarisation directions are often termed SV and SH to denote vertical and horizontal orientations; however, these orientations need not be with respect to the incident plane. SH and SV always refer to a reference plane [4], and in one case the reference plane coincides with our block coordinates and on the other it does not.

A video illustrating the pulse travel directions is provided with this paper. Click here:

https://www.ndt.net/?id=25799

References

1. Holloway, P., Ginzel, E., Calibration for Anisotropic Effects on Shear Wave Velocity for Improvements of Weld Inspections in TMCP steels, www.NDT.net, February 2021
2. Keiji, I.B.A., Method of Ultrasonic Angle Beam Examination for Welds of Ferritic Steel s with Acoustic Anisotropy, Activity Report of Non-destructive Inspection Subcommittee Quality Control Committee, The Joint Research Society, ISIJ, Volume 27 Issue 11, 1987
3. Heyliger, P., Ledbetter, H., Kim, S., Elastic Constants of natural quartz, Journal of the Acoustical Society of America, Volume 114, No. 2, 2003
4. Langenberg, K., Marklein, R., Mayer, K., Ultrasonic Nondestructive Testing of Materials, Theoretical Foundations, ISBN 13: 978-1-4398-5590-4, CRC Press, Taylor & Francis Group, 2012