Birefringence measurements in single crystal sapphire and calcite shocked along the a axis

Gareth R. Tear, David J. Chapman, Daniel E. Eakins, and William G. Proud

Citation: AIP Conference Proceedings **1793**, 060005 (2017); doi: 10.1063/1.4971561
View online: https://doi.org/10.1063/1.4971561
View Table of Contents: http://aip.scitation.org/toc/apc/1793/1
Published by the American Institute of Physics

Birefringence Measurements in Single Crystal Sapphire and Calcite Shocked Along the *a* Axis

Gareth R Tear[1,a)], David J Chapman[1], Daniel E Eakins[1] and William G Proud[1,b)]

[1] *Institute of Shock Physics, Imperial College London, Blackett Laboratory, Prince Consort Road, London, SW7 2BW, UK*

[a)] Corresponding author: g.tear12@imperial.ac.uk
[b)] w.proud@imperial.ac.uk

Abstract. Calcite and sapphire were shock compressed along the $\langle 1\,0\,\bar{1}\,0\rangle$ direction (*a* axis) in a plate impact configuration. Polarimetery and Photonic Doppler Velocimetery (PDV) were used to measure the change in birefringence with particle velocity in the shock direction. Results for sapphire agree well with linear photoelastic theory and current literature showing a linear relationship between birefringence and particle velocity up to 310 m s^{-1}. A maximum change in birefringence of 5% was observed. Calcite however showed anomolous behaviour with no detectable change in birefringence (less than 0.1%) over the range of particle velocities studied (up to 75 m s^{-1}).

INTRODUCTION

Measurements of a material's optical properties under shock compression have been performed for decades beginning with transmission and reflection measurements [1]. More recently measurements of refractive index and the complex dielectric constant have been performed through velocimetry [2] and ellipsometry methods [3]. These measurements are important for calibrating optical window materials as experimental standards [4] and to understand the changes in electronic structure that occur under shock compression. In highly anisotropic materials the elastic and optical properties vary with material orientation and effects such as birefringence can be observed. This effect has been investigated under shock compression in window materials by [5, 4].

Under static and steady state loading conditions the elastic and optical behaviour of linear homogenous anisotropic materials is mathematically well developed [6, 7]. As birefringence is a property that is caused by optical anisotropy, to test the application of linear photoelastic theory under shock loading conditions the birefringence was measured as a function of particle velocity. In this set of experiments calcite and sapphire were shocked along their *a* axis and a polarimeter was used to measure the change in birefringence. Linear photoelastic theory, along with static photoelastic data, has been used to predict the expected change in birefringence, and comparison between expected and measured results are made.

EXPERIMENTAL METHOD

Plate impact experiments were performed in a direct impact configuration on the Institute of Shock Physics (ISP) 100 mm bore light gas gun. Samples were impacted to generate a single elastic wave in the sample. An illustration of the experimental configuration is shown in figure 1. Samples were 25 mm square with a nominal thickness of 8 mm. The thickness of each sample was measured to 3 μm precision and the front and rear surfaces were determined to be parallel to at least 1 mrad. A 500 nm reflective aluminium coating was deposited on the impact surface and an anti-reflective (AR) coating was applied to the rear surface. The AR coating was optimised for 532 nm light with a reflectivity of less than 2%. The initial birefringence Δn was measured prior to the experiment at several locations. By considering the value of Δn at different locations crystallogrpahic tilt was found to be within the manufacturing tolerance of $\pm 2^{\circ}$, though could not be measured with greater precision.

Shock Compression of Condensed Matter - 2015
AIP Conf. Proc. 1793, 060005-1–060005-5; doi: 10.1063/1.4971561
Published by AIP Publishing. 978-0-7354-1457-0/$30.00

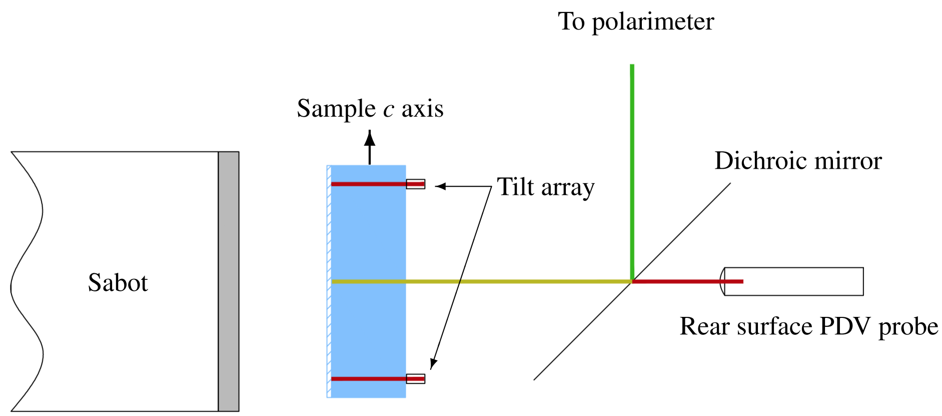

FIGURE 1. Illustration of the experimental geometry (not to scale). The flyer thickness was nominally 8 mm and the rear surface probe stand off 140 mm. Dichroic mirrors from Knight Optical were used to separate the polarimeter beam from the PDV probe. An aluminium back plate (not shown) was used to mount the sample, PDV probes and dichroic mirror to the target ring.

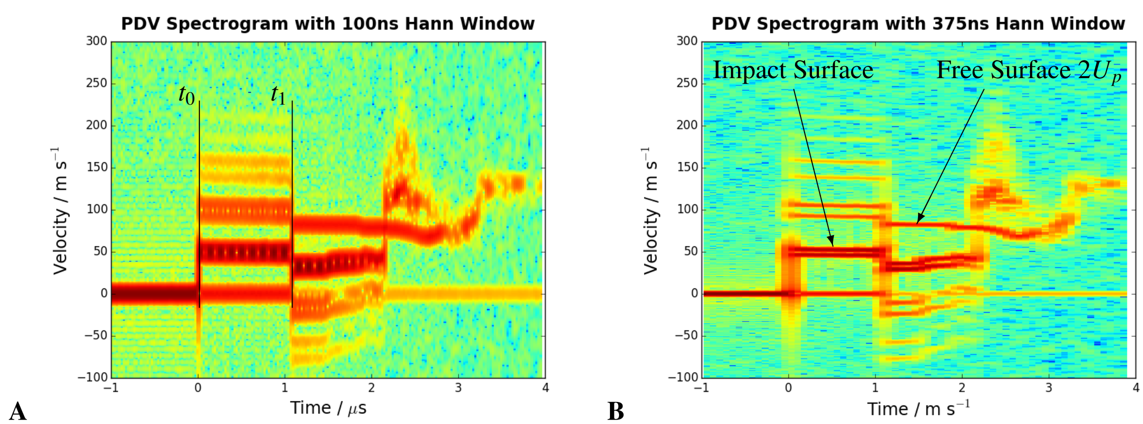

FIGURE 2. PDV spectrograms from the same dataset (calcite shot 2, see table 1). **A** uses a short window for determining shock velocity U_s from the impact time t_0 and breakout time t_1 whilst **B** uses a long window to determine particle velocity U_p, taken to be half the free surface velocity. Due to the birefringent nature of calcite, the reflection from the impact surface results in two different frequencies present in the spectrogram.

Photonic Doppler Velocimetery (PDV)

PDV was used to determine the projectile velocity, impact tilt, rear surface velocity and impact surface velocity. Two collimating −60 dB probes with a 500 μm spot size were used per experiment, one for the projectile velocity and the other for the rear/impact surface probe. An array of 4 bare straight ferrule connector (FC/PC) patch fibres were used to measure tilt. As the sample AR coating is optimised for 532 nm and the PDV system operates at 1550 nm, significant signal was reflected from the rear surface. The rear surface probe was sampled at 40 GS s^{-1} on a 16 GHz bandwidth oscilloscope for 100 μs.

Polarimetery

Polarimetery was used to measure the polarisation of light that had been transmitted through the sample. Previously in [8] a two channel polarimeter was used, however a number of improvements have been made. Previously a polarising beam splitting cube was used, which does not have identical extinction ratios for S and P polarisations and are nominally 100:1 and 50:1. This was replaced with a wollaston prism which has 10000:1 for both orientations. A pair of orthogonal circular detectors was also added and circular input polarisation was used to ensure that the measurement was not sensitive to rotation around the shock axis. Hence a four channel polarimeter was used with two orthogonal

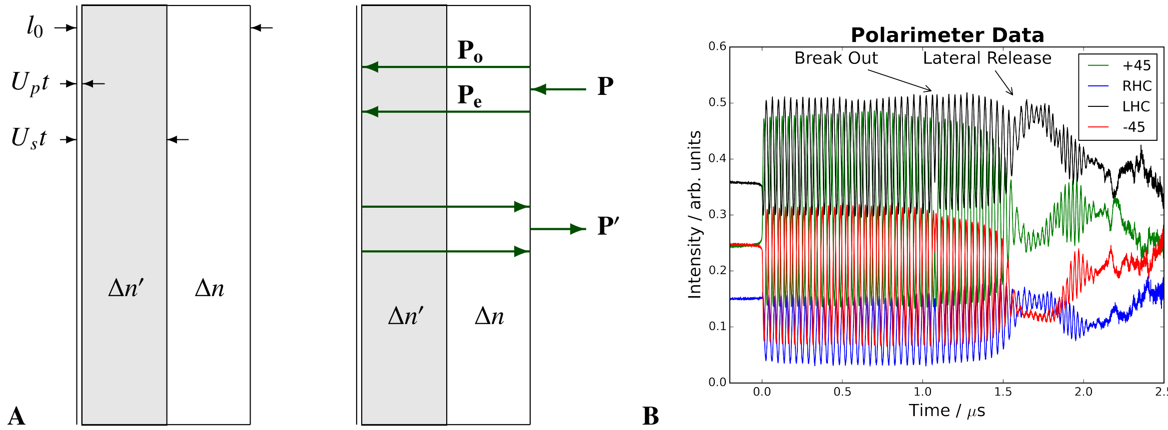

FIGURE 3. **A** Illustration of shock propagation model, used to derive equation 1. An input polarisation state **P** propagates as two orthogonal polarisations $\mathbf{P_o}$ and $\mathbf{P_e}$ in the birefringent material. The emerging polarisation state $\mathbf{P'}$ is a function of the phase difference between $\mathbf{P_o}$ and $\mathbf{P_e}$, which is in turn dependant on the shocked birefringence $\Delta n'$ and the positions of the interfaces given by $U_s t$ and $U_p t$ where time is t. $\mathbf{P'}$ can be measured with a polarimeter, example data from shot 2 in table 1 is shown in **B**.

circular and two orthogonal linear channels with detectors of bandwidth 1 GHz. The optical source was a Coherent Verdi laser with wavelength λ of 532 nm and output power of 0.7 W. Spot size for the polarimeter was 5 ± 1 mm.

POLARIMETER ANALYSIS

It was assumed that the shock compression process could be modelled as a single step wave propagating through the sample at a constant velocity. The rear surface PDV data was used to verify the single wave assumption. The raw data was processed using the sliding short time fourier transform with 100 ns and 375 ns Hann windows to produce two spectrograms, shown in figure 2. These were used to find both the shock velocity U_s and the particle velocity U_p respectively, which was required to find the shocked birefringence in equation 1.

From the polarimeter, data such as that in figure 3 was obtained and the frequency of observed oscillations f found using a fast fourier transform. This, combined with parameters obtained from the PDV, was used to calculate the shocked birefringence $\Delta n'$ using equation 1, where Δn is the unshocked birefringence.

$$\Delta n' = \frac{f\lambda + 2U_s\Delta n}{2(U_s - U_p)} \tag{1}$$

RESULTS AND DISCUSSION

The PDV data were analysed for each shot to obtain shock, particle and impact velocities for each experiment and these values are listed in table 1, along with expectations from impedance matching calculations and existing literature Hugoniots [9, 10, 4]. Comparison between experimental values obtained here and previous literature values show good agreement. Following the analysis of the previous section a change in birefringence with particle velocity was obtained for each experiment. These results are presented in figure 4 with predictions generated using linear photoelastic theory [7].

Whilst the results for sapphire are in agreement with [4] and linear photoelastic theory (with values taken for synthetic sapphire [11]), the calcite results are anomolous when compared to static literature [12, 13]. Previous measurements put the longitudinal stress Hugoniot Elastic Limit (HEL) at 1.85 GPa for the c-axis [10]. Later experiments suggested that this was the calcite - calcite-II phase transition [14, 15] though this has been observed at a hydrostatic pressure of 1.45 GPa in hydrostatic experiments [16, 17]. The longitudinal stresses in the present work range from 0.82 GPa to 1.51 GPa, below the expected calcite - calcite-II phase transition implying samples remained elastic. This is backed up by PDV data which shows no multiwave structure as would be expected if there was a phase transition. It seems reasonable to assume the sample remained elastic so it was expected that the data would match the prediction.

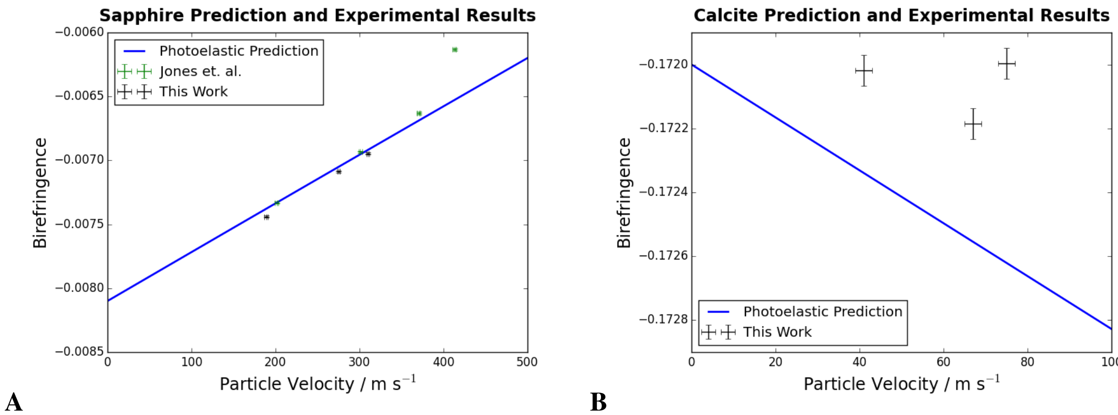

FIGURE 4. Calculated birefringence from polarimeter data $\Delta n'$ for **A** sapphire and **B** calcite. Predictions made using linear photoelastic theory and static photoelastic data from [11] for sapphire and [12] for calcite have been added for comparrison. **A** has data from [4] for comparrison. It can be clearly seen that **B** does not follow either prediction.

TABLE 1. Experimental shot parameters measured using PDV. Birefringence is calculated from polarimeter data and data listed here using equation 1. PDV data here agrees with Hugoniot data for calcite [10] and sapphire [4] available in the literature. Predicted U_p is found using flyer Hugoniots in [9]

N	Target	Flyer	V / m s^{-1}	U_p / m s^{-1}	U_s / km s^{-1}	Predicted U_p / m s^{-1}	$\Delta n'$
1	Calcite	Mg AZ31B	206	67	7.42	62	-0.17219
2	Calcite	PMMA	262	41	7.39	35	-0.17202
3	Calcite	Mg AZ31B	255	75	7.42	76	-0.17200
4	Sapphire	Cu 1001	414	189	11.38	191	-0.00744
5	Sapphire	Cu 1001	600	275	11.60	282	-0.00709
6	Sapphire	Cu 1001	657	310	11.63	309	-0.00695

Given that the anomoly cannot be explained by the phase transition, future work will investigate this behaviour further. Previously elastic constants up to third order have been used for calcite [14], however as the elastic constants are needed to calculate the photoelastic tensor, a non-linear elastic model would require a non-linear photoelastic model to remain consistent. Developing this may explain the inconsistency.

CONCLUSIONS

Sapphire has been shown to behave according to linear anisotropic elastic and photoelastic theory, using static measurements from literature. Results for calcite do not agree with linear photoelastic theory, as well as showing an anomolous zero change in birefringence with strain. The cause of this effect, not observed in static experiments, is thought to be due to non-linear elasticity.

ACKNOWLEDGMENTS

The institute of shock physics recognises the continued support of AWE and Imperial College London.
The authors would like to thank Mr David Pitman and Mr Steve Johnson for technical support.
Gareth R Tear would like to thank the Institute of Physics (IOP) and the American Physical Society (APS) for travel grants allowing him to travel to the conference.

REFERENCES

[1] S. B. Kormer, Physics-Uspekhi **11**, 229–254 (1968).

[2] L. M. Barker and R. E. Hollenbach, J. Appl. Phys. **41**, p. 4208 (1970).
[3] C. a. Bolme, S. D. McGrane, D. S. Moore, and D. J. Funk, J. Appl. Phys. **102** (2007).
[4] S. C. Jones, B. A. M. Vaughan, and Y. M. Gupta, J. Appl. Phys. **90**, p. 4990 (2001).
[5] J. H. Nguyen and N. C. Holmes, "Shock-Induced Birefringence in Lithium Fluoride," in *Shock Compression Condens. Matter*, Vol. 620, edited by M. D. Furnish, N. N. Thadhani, and Y. Horie (Atlanta, 2002), pp. 1251 – 1254.
[6] T. C. T. Ting, *Anisotropic Elasticity: Theory and Applications*, 1st ed., edited by J. M. Brady, C. E. Brennen, W. R. Eatock Taylor, M. Y. Hussaini, T. V. Jones, and J. Van Bladel (Oxford University Press, New York, 1996).
[7] A. Yariv and P. Yeh, *Optical Waves in Crystals*, 1st ed. (John Wiley & Sons, New York, 1984) p. 318.
[8] G. R. Tear, D. E. Eakins, D. J. Chapman, and W. G. Proud, in *Shock Compression Condens. Matter*, Vol. 500 (Journal of Physics: Conference Series, Seattle, 2014) p. 2020.
[9] S. P. Marsh, ed., *LASL Shock Hugoniot Data*, 1st ed. (University of California Press, Los Angeles, 1980).
[10] T. J. Ahrens and V. G. Gregson, J. Geophys. Res. **69**, 4839–4874 (1964).
[11] J. Reintjes and M. B. Schulz, J. Appl. Phys. **5254** (1968).
[12] D. F. Nelson, P. D. Lazay, and M. Lax, Phys. Rev. B **6**, 3109 – 3120 (1972).
[13] D. P. Dandekar, J. Appl. Phys. **39**, p. 2971 (1968).
[14] B. S. Stapleton, "Response of single crystal calcite shocked to 40 kbar along the c-axis," Msc thesis, Washington State University 1990.
[15] D. E. Grady, in *Shock Waves Condens. Matter*, edited by Y. Gupta (Springer US, Spokane, WA, 1986), pp. 589–593.
[16] P. W. Bridgman, Am. J. Sci. **237**, 7–18 (1938).
[17] A. K. Singh and G. C. Kennedy, J. Geophys. Res. **79**, 2615–2622 (1974).