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INDEX OF REFRACTION MEASUREMENTS AND WINDOW CORRECTIONS FOR PMMA UNDER SHOCK COMPRESSION

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Abstract. Symmetric plate impact experiments were performed to investigate the change in the refractive index of Polymethylmethacrylate (PMMA) under shock loading. Flyer and target geometries allowed the measurement of shock velocity, particle velocity, and refractive index in the shocked state, using a Het-V system (1550 nm). The change in refractive index of PMMA as a function of density is generally considered to be well described by the Gladstone-Dale relationship, meaning that the "apparent" velocity measured by a laser velocity interferometer is the "true" velocity, and hence there is no window correction. The results presented here demonstrate that the behaviour of PMMA deviates from an ideal Gladstone-Dale description, requiring a small velocity correction of order 1% at peak stresses up to 1.9 GPa. These results are consistent with literature values measured using a wavelength of 632.8 nm by [1].

Keywords: Refractive index, Window, PMMA

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INTRODUCTION

In a uniaxial strain dynamic compression experiment we typically monitor the interface velocity between the sample and an optically transparent window which maintains the high stress state. In this case it is necessary to know both the optical and mechanical properties of the window in order to determine the behaviour of the sample. In velocity interferometry measurements employing a window, the apparent interface velocity u_a is in general different to the actual interface velocity u . The difference between these velocities, referred to as the velocity correction δu , is a result of the changing optical thickness of the window [2]. There are two competing factors which contribute to the overall change in the optical thickness of the window; 1) the compression of the window which leads to a reduction in the physical window thickness and 2) the change, generally an increase, in refractive index of the window as a result of the compression.

The velocity correction is a constant factor for

both steady and unsteady simple compression waves in the window whenever the index of refraction of the window is linear function of density [2]. The shocked refractive index and velocity correction have been well characterised for a number of window materials, for example LiF(100), z-cut quartz, c-cut sapphire, at a number of wavelengths, for example 1550 nm (relevant to Het-V) and 532 nm (relevant to VISAR) [3]. However, these window materials are of relatively high shock impedance, while often it is desirable to use a lower impedance window such as PMMA. While PMMA has seen widespread use as window during dynamic loading experiments, the velocity correction, particularly given the rate dependant response of the material, remains relatively under investigated, with the work presented by Barker and Hollenbach being the only complete investigation available in the open literature [1]. They demonstrated that the velocity correction was not a constant, but lay between -0.0022 and -0.0117 in the particle velocity range 0.032 to 0.3172 km s⁻¹ for a laser wavelength of 632.8 nm. To date no equivalent

investigation has been published which is relevant to Het-V. Het-V, operating at 1550 nm, is rapidly becoming a standard diagnostic for measuring velocities in dynamic compression research, and given that the window correction is a function of wavelength for other window materials such as LiF and sapphire [3] there is a practical need to measure the window correction of PMMA at 1550 nm.

This paper details results from an ongoing investigation into the velocity correction in a particular brand of PMMA, Perspex GS. Judicious selection of flyer and target geometries allowed the measurement of shock velocity, particle velocity, sound speed in the shocked state, and refractive index in the shocked state in addition to the velocity correction.

EXPERIMENTAL METHOD

FIGURE 1. Experimental configuration used to measure the velocity correction indicating the various reflections which contribute to the Het-V signal; a) before impact, b) short time after impact showing the propagation of shock waves in the impactor and target.

The experimental configuration employed in the present study is described in figure 1, and represents a subtle modification to the classic geometry suggested by Lalone *et al.* [2]. In the modified configuration a thin PMMA flyer (4.5 mm thick) impacts a thick (12 mm) PMMA target. The impact and target discs were manufactured from Perspex GS sheet, machined to the desired thickness, and optically polished. A Het-V system [4] monitors the velocity history of a mirror evaporated on to the rear surface of the flyer. Before impact, the velocity of the mirror is simply the velocity of the projectile, V . Figure 1b describes the scenario a short time after impact, where shock waves are propagating in both the im-

FIGURE 2. Typical STFT power spectrum obtained during a symmetric plate-impact at 373 m s^{-1} using an upshifted Het-V system (labels explained in the main text).

pactor and target. The velocity of the mirror remains unchanged, however the apparent velocity measured by the Het-V system corresponds to an optical path involving the shock compressed material in both the impactor and target, and hence is the sum of the projectile velocity and twice the correction for a single window in the standard experiment [2]

$$V_a = V + 2\delta u. \quad (1)$$

The shocked refractive index in the specimen n_s is then related to the apparent velocity, initial refractive index n_0 and shock-velocity D according to [3]

$$u_a = n_0 D - n_s (D - u) \quad (2)$$

This configuration improves the resolution of the correction factor particularly for materials such as PMMA where the velocity corrections are almost negligible. In total five plate-impact experiments were conducted using the 50 mm bore 5 m length single stage light gas gun at the University of Cambridge. Impact velocities were measured using the Het-V system and the target was aligned with the impactor by means of an adjustable specimen mount resulting in a typical impact tilt of less than 2 mrad.

One experiment was performed using a conventional Het-V configuration and the remaining four of the five experiments conducted using an upshifted Het-V system. In both Het-V configurations, an IPG Photonics laser operating near 1549.97 nm illuminated the target. In the conventional Het-V system this laser also served as the reference frequency. For the upshifted configuration a second laser, NP Pho-

tonics "Rock" operating at a slightly longer wavelength was used as the reference frequency. Light was delivered and collected from the target using an Oz optics collimating probe with -60 dB back reflectance and measured with a 12.5 GHz bandwidth receiver sampled at 50 GS/s. In both configurations the signal frequency increased with motion towards the probe, however the upshifted Het-V signal started with a base beat frequency of order 5.4 GHz while the conventional Het-V started at zero frequency.

RESULTS

Figure 2 shows a typical STFT power spectrum obtained demonstrating the complex array of velocities and interfaces monitored by the single Het-V probe. The figure identifies the zero velocity beat frequency (in terms of velocity) for the upshifted system, A, the impact velocity, B, and the feature associated with the velocity correction occurring at the moment of impact, C. The figure also shows in chronological order the particle velocity history at the impact plane, D, arrival of the shock wave at the location of the mirror on the rear surface of the flyer, E, the subsequent arrival of the release fan at the impact plane, F, and finally the arrival of the shock wave at the rear of the target, G.

The projectile velocity and apparent velocity after impact were extracted from the upshifted Het-V signals using a Hamming window function, a time duration of 41 ns, and 10120 frequency points in the STFT analysis. The conventional Het-V signal was analysed with a slightly longer window of 51 ns. The relatively long analysis windows were necessary to distinguish between the various Fresnel window reflections and provide an accurate determination of the projectile and apparent velocities (0.2-0.7%) in the presence of the other velocity signals such as that from the impact plane. The uncertainty in the velocity was determined from half of the difference between the minimum and maximum velocity measured during the region of interest. This requires that the shock wave propagating, and hence optical path through which the measurement is made, is steady. This is known not to be the case for PMMA where its behaviour involves nonlinearity, and strain-rate dependence [1]. This behaviour results in the typical wave profile observed at the free surface in figure

FIGURE 3. Measured shock velocity and rarefaction wave velocity as a function of particle velocity.

FIGURE 4. Measured velocity correction as a function of particle velocity.

2, where a discontinuous shock is followed by an asymptotic approach to a steady state, or equilibrium particle velocity. For the present study, this behaviour should result in an optical path difference which is itself a function of time, meaning the velocity correction may exhibit some time dependence. Experimentally this is not resolved in the results presented here, and hence the velocity correction is considered to be measured at the equilibrium particle velocity state given by half of the measured impact velocity. Future experiments involving different target and diagnostic configurations aim to explore this feature.

Figure 3 shows the shock velocity, and Lagrangian velocity of the leading tail of the rarefaction fan obtained from the measured time of arrivals and the target and impactor thicknesses. Equilibrium particle velocity was obtained from half of the measured projectile velocity. The measured shock-velocity data agree with the data obtained by Barker and Hollen-

FIGURE 5. Measured shocked refractive index versus shocked refractive index calculated using the Gladstone-Dale relationship. The solid black line indicates perfect Gladstone-Dale behaviour.

bach [1], showing the nonlinear shock-velocity particle velocity dependence. The measured rarefaction velocities are not in as good agreement as a result of the difficulty in defining the time of arrival of the release fan at the impact plane due to the weak signal reflected from this interface.

WINDOW CORRECTION

Figure 4 shows the measured window correction using the Het-V system as a function of equilibrium particle velocity. The figure also presents the data obtained by Barker and Hollenbach using a wavelength of 632.8 nm and a different brand of PMMA. The two data sets are in close agreement demonstrating that a velocity correction in the region of 1% is appropriate.

Figure 5 plots the shocked refractive index calculated using equation 2 (using the measured velocity correction) versus the shocked refractive index calculated assuming the Gladstone-Dale relationship given by equation 3 [5]. The index of refraction and density of the investigated PMMA were 1.481 at 1550 nm [6] and $1.186 \pm 0.001 \text{ g cm}^{-3}$ respectively. The figure presents the refractive index data obtained by Barker and Hollenbach at 632.8 nm for comparison, and clearly demonstrates that both experimental data sets are well described by the Gladstone-Dale relationship.

$$n_{sGD} = 1 + (n_0 - 1)/(1 - u/D) \quad (3)$$

SUMMARY

Symmetric plate-impact experiments were performed in the velocity range 200–960 m s^{-1} with the primary objective of measuring the window correction for PMMA at a wavelength of 1550 nm using conventional and upshifted Het-V systems. The measured signals enabled the simultaneous determination of shock velocity, particle velocity, density in the shocked state, and refractive index in the shocked state, in addition to the desired window correction at stresses up to 1.9 GPa. The measured window correction for PMMA at a wavelength of 1550 nm was found to be a function of particle velocity and not constant in the investigated regime. The measured velocity corrections were of order 1%, which is consistent with data previously obtained by Barker and Hollenbach at a different wavelength, and with the assumption that PMMA is well described by a modified Gladstone-Dale relationship.

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REFERENCES

1. Barker, L.-M., and Hollenbach, R.-E., *J. Appl. Phys.*, **41**, 4208–4226 (1970).
2. LaLone, B. M., Fat'yanov, O. V., Asay, J. R., and Gupta, Y. M., *Journal of Applied Physics*, **103**, 093505 (2008).
3. Jensen, B. J., Holtkamp, D. B., Rigg, P. A., and Dolan, D. H., *Journal of Applied Physics*, **101**, 013523 (2007).
4. Strand, O.-T., *Review of Scientific Instruments*, **77** (2006).
5. Wise, J., and Chhabildas, L., "Laser interferometer measurements of refractive index in shock compressed materials," in *Shock Waves in Condensed Matter U 1985*, edited by Y. Gupta, Plenum, New York, 1986, pp. 441–454.
6. Kasarova, S. N., Sultanova, N. G., Ivanov, C. D., and Nikolov, I. D., *Optical Materials*, **29**, 1481 – 1490 (2007).