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Shock Characterization of Quartz Phenolic Composite

L. J. Weirick, L. C. Chhabildas

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SHOCK CHARACTERIZATION OF QUARTZ PHENOLIC COMPOSITE*

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Abstract

The goal of this program was to obtain dynamic mechanical property data on a quartz phenolic (abbreviated QP) composite. Shock loading and shock release measurements have been conducted using impact techniques utilizing both a light-gas gun and a powder gun at impact pressures up to 20 GPa. The primary diagnostic tool used was a velocity interferometer. The data analysis includes Hugoniot measurements to give both pressure-particle velocity and shock velocity-particle velocity relationships; spall measurements to determine the fracture stress at which the material spalls; and attenuation measurements to determine the shock attenuation with material thickness. The QP Hugoniot relationship was found to be significantly different than that of a phenolic without a filler material indicating that the impedance of the QP used in this investigation was higher. The spall strength was measured to be ~ 0.075 GPa, similar to non-filled phenolic, which indicated that the presence of quartz fibers was not contributing to the fracture strength. The material was found to attenuate an imposed shock of approximately 6.3 GPa pressure and $0.18 \mu\text{s}$ to 50% of the initial impact value after a propagation distance of 7mm.

*The work described in this report was performed by Sandia National Laboratories for the United States Department of Energy under contract #DE-AC04-94AL85000.

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Introduction

The need exists for time-resolved equation of state (EOS) data for QP composite in the space communities within the DOE, DoD and NASA. Although the material is primarily used as nose cones on space-based reentry vehicles, there is very little time-resolved data available to characterize its mechanical properties. The main objective of the present set of high precision experiments is to develop a material model for use in hydrodynamic codes such as the CTH code developed at Sandia National Laboratories. The first step, in arriving at a material model, is to conduct experiments such as those reported in this report which provide the dynamic mechanical properties of the material. Results of these experiments are expected to serve as a data base to achieve this goal. These experiments are the first time-resolved interferometric measurements ever performed above ~2 GPa on QP.

A significant number of studies were done on various lay-ups of quartz loaded phenolic back in the early '70's. These studies included investigations of one, two, and three-dimensionally woven quartz phenolics. The most extensive work on a two-dimensionally woven material presumably similar to the presently investigated material was done by Munson[1]. Munson reported two Hugoniot relationships for the equation of state of 2-D Quartz phenolic at particle velocities up to 2 mm/ μ s. His reported Hugoniot relationships are as follows:

$$U_s = 3.15 + 1.4 U_p - 0.29 U_p^2 \quad \text{for } 0 < U_p < 1.0 \text{ mm}/\mu\text{s} \quad (1)$$

$$U_s = 3.10 + 1.06 U_p \quad \text{for } 1 < U_p < 2.0 \text{ mm}/\mu\text{s} \quad (2)$$

where U_s is the shock velocity and U_p is the particle velocity. The technique that Munson used was to measure pressure and then calculate particle velocity for a given experiment utilizing quartz or manganin gauges, quartz up to particle velocities of 0.4 mm/ μ s and manganin at higher values. Munson's results are indicated in Figure 1 both as data points and the above U_s , U_p Hugoniot relationships for the regions correlated with the two gauges. Munson's reported values are an average of the data from the two gauge regions. With the advent of laser interferometry, a direct measurement of particle velocity is possible, thus allowing a re-investigation of these Hugoniot relationships more directly.

Experimental Procedure

Material

The material is a phenolic composite containing a bi-directional quartz weave. It is manufactured by stacking up the weaves by layer and impregnating with phenolic resin. The nominal density of the QP is 1.71 g/cm³ compared to 1.385 g/cm³ for non-filled phenolic. The sheet from which the samples were made was examined by ultrasonic radiography and found to be without significant porosity or delamination. Longitudinal and shear velocity measurements were made on each of the samples. These measurements also indicate that the raw material sheet was fairly

uniform and isotropic. The samples were nominally 50 mm in diameter and 12.7 mm thick, right-circular cylinders. The samples were made with the weave parallel with the front face.

Sound Velocity Measurements

Bulk sound velocity measurements were done on the material using a 5 MHz source for the longitudinal velocity measurements and a 1 MHz source for the shear velocity measurements. The measurements were made perpendicular to the weave. The results are indicated in Table 1. The average longitudinal velocity was found to be 3.47 mm/ μ s and the average shear velocity was found to be 1.92 mm/ μ s. Using the following equation which relates longitudinal and shear velocity to the bulk sound velocity:

$$C_b^2 = C_l^2 - 4/3 C_s^2 \quad (3)$$

the average bulk sound velocity for the present material was calculated to be 2.67 mm/ μ s.

Gas Gun

The light-gas gun system used is described in detail in Reference 2. Briefly, the barrel is 9 meters long, with an inside diameter of 63.4 mm. The breech is of a quick-acting, quick-change design with two inserts; one termed a "wrap-around" for low-velocity shots utilizing nitrogen (below 0.5 km/s) and a second called a "dual-diaphragm" for higher-velocity shots using helium (up to 1.5 km/s for projectiles with mass below 0.2 kg).

Powder Gun

The powder gun system used is located at the Shock Thermodynamic Advanced Research (STAR) Facility[3]. Briefly, the barrel is 10 meters long, with an inside diameter of 89 mm. Velocities up to 2.4 km/s can be obtained for 1 kg projectiles.

VISAR

One modern technique used for measurement of shock phenomena is the Velocity Interferometer System for Any Reflector referred to as VISAR[4]. A "Push-Pull" VISAR method developed by Hemsing[5] and used in these experiments results in effective cancellation of light intensity changes during the measurement. In addition, the return laser light is divided between two interferometer legs (dual-leg) with different calibration factors to insure the proper measurement of peak particle velocities.

Projectile/Targets for Hugoniot Measurements

A schematic of the projectile/target configuration for Hugoniot experiments is shown in Figure 2. QP specimens (12.7 mm thick) were mounted on the front of nylon/foam sabots. The QP

specimens acted as flyer plates in impacts with the target materials. The target materials were either polymethyl methacrylate (Polycast), fused silica, or sapphire with known Hugoniot relationships[6,7]. Polycast is the presently available version of PMMA whose Hugoniot relationship was recently determined by Matthews and Weirick[8] and was found to be experimentally identical to PMMA. The targets consisted of both a thin, 1 mm, buffer plate and thicker, 12.7 mm, window of the same material. The window had a 0.1 mm thick layer of vapor-deposited-aluminum on the front which reflected the laser beam for the VISAR. The particle velocity measurements were made at the buffer/window interface

Projectiles/Targets for Release Measurements

A schematic of the projectile/target configuration for release experiments is shown in Figure 3. Sapphire impactors (6.35 mm thick) were used to impact the QP targets. The 7 mm thick QP targets had a 0.5 mil thick foil of aluminum epoxied on the rear of the sample surface which acted as a laser reflector. A 12.7 mm thick disc of PMMA was epoxied to the aluminum foil and used as a laser window. Measurements of particle velocity were made at the interface between the aluminum foil and the PMMA window.

Projectiles/Targets for Attenuation Measurements

A schematic of the projectile/target configuration for attenuation experiments is shown in Figure 4. The projectile had a 1 mm thick sapphire flyer backed with low-density (0.2 g/cm^3) carbon foam (6.35 mm thick) mounted on the front of aluminum sabots. The target material was QP with thicknesses of either 4 or 7 mm. Aluminum foil was epoxied on the rear of the QP as a laser reflector. A 12.7 mm thick window of PMMA completed the target. Particle velocity measurements were made at the interface between the aluminum foil and the PMMA window.

Projectiles/Targets for Spall Measurements

A schematic of the projectile/target configuration for the spall experiment is shown in Figure 5. The projectile had a 6.35 mm thick sapphire flyer backed with the low-density carbon foam, 6.35 mm thick. The QP target was 7 mm thick with aluminum foil on the free surface and did not have a backing window. Free-surface velocity measurements were made at the back surface of the aluminum foil.

Projectiles/Targets for Release Measurements on the Powder Gun

A schematic of the projectile/target configuration for the release experiments on the powder gun is shown in Figure 6. Sapphire flyer plates of 6.35 mm thickness backed with 6.35 mm thick carbon foam were mounted on phenolic sabots. The QP targets were 4 mm thick with aluminum foil reflectors on the back with 12.7 mm thick PMMA windows. Particle velocity measurements were made at the interface between the aluminum foil and PMMA window.

Results

Table 2 gives a summary of the conditions used for the various experiments. The information given includes shot number, impactor material and thickness, target or buffer material and thickness, window material and thickness, the measured projectile velocity, and the maximum measured particle velocity at the buffer/window or target/window interface. Figures 7-9 give a compilation of the velocity interferometer, VISAR, data shown as particle velocity at the buffer/window or target/window interface as a function of time for the various types of experiments. Figure 7 is a compilation of the Hugoniot shots done on the gas gun. Figure 8 is a compilation of the release shots done on the gas gun, while Figure 9 is the data obtained for release shots on the powder gun.

Table 3 summarizes the calculated results from the Hugoniot shots on the gas gun. These results include the calculated particle velocity in the QP, the calculated pressure of the impact, and the calculated shock velocity in the QP. The particle velocity in the QP was calculated from the following relationship:

$$U_p(QP) = \text{Projectile Velocity} - U_p(\text{target}) \quad (4)$$

where Projectile Velocity is the measured projectile velocity and $U_p(\text{target})$ is the particle velocity measured in the target (buffer/window) at the buffer/window interface. (These measurements are given in Figure 7). Conservation of mass and momentum requires that the impact pressure be the same in the target (buffer/window) and the QP phenolic. Therefore, the impact pressure was calculated knowing the projectile velocity, the particle velocity in the target, and the Hugoniot relationship for the target material. The relationship used was [5]:

$$P(\text{target}) = \rho_0(\text{target}) \times U_p(\text{target}) \times U_s(\text{target}) \quad (5)$$

where $\rho_0(\text{target})$ is the initial density of the target material and $U_s(\text{target})$ is the shock velocity in the target known from the Hugoniot relationship for the target. Knowing the stress and the particle velocity in the QP, allows the calculation of the shock velocity in the QP using the relationship:

$$U_s(QP) = P/\rho_0(QP) \times U_p(QP) \quad (6)$$

where $\rho_0(QP)$ is the initial density in the QP specimen.

Pressure versus Particle Velocity in the QP

The particle velocity in the QP for a given impact pressure is summarized in Table 3. Figure 10 is a plot of particle velocity in the QP versus impact pressure for the three types of experiments done. This relationship is also compared in the figure to that known for non-filled phenolic[5].

Hugoniot Relationship for QP

As outlined in a previous section, the shock velocity in the QP can be calculated for a given impact pressure if the initial density and particle velocity are known. These values are summarized in Table 3 for the Hugoniot shots. Figure 11 shows the plot of particle velocity versus shock velocity in the QP. From this plot, a linear Hugoniot relationship can be determined. The Hugoniot relationship is[5]:

$$U_s = C_0 + S U_p \quad (5)$$

where C_0 is the intercept of the linear relationship with the "0" particle velocity axis and is also associated with the initial "bulk" sound velocity. The slope of the linear relationship is designated S . In the present study, the values of C_0 and S were determined to be 2.62 mm/ μ s and 1.90, respectively. The value of 2.62 mm/ μ s for C_0 agrees very well with the value of 2.67 mm/ μ s previously calculated as the bulk sound velocity from the ultrasonic measurements. This Hugoniot relationship is compared in Figure 11 with the Hugoniot published for non-filled phenolic, where C_0 and S are 2.99 mm/ μ s and 1.40, respectively. [6]

Attenuation within QP

Specifications for gas gun shots to determine attenuation in the QP are given in Table 2. A plot of the decrease in particle velocity (measured at the QP target/PMMA window interface) for a given impact pressure of approximately 6.3 GPa as a function of the thickness of the QP is given in Figure 12. Shot 414 is the baseline value for no attenuation, since the impactor was thick and gave a relatively long impulse, 1.12 μ s. It can be seen that the shock pulse decreases almost 50% within the first 7 mm of QP material.

Spall Strength of QP

Specifications for the gas gun shot to determine the value for spall in the QP are given in Table 2. Figure 13 shows the curve of free surface velocity versus time from which the spall strength of QP was determined. This record of free surface velocity was taken off the back side of a QP specimen impacted at ~ 0.77 GPa with a sapphire impactor. The change in free surface velocity or "pullback" is indicated. This value of pullback is used in the following equation to calculate the spall strength [9].

$$\sigma_s = 1/2 C_0 \rho_0 U_F \quad (6)$$

where σ_s is the spall strength, ρ_0 the initial density and U_F is the measured value of pullback. The maximum value of spall strength calculated for QP was 0.077 GPa (0.77 kbar). This is an upper bound because of the uncertainty in "estimating" an equilibrium maximum free surface velocity.

Shock Release States

Experiments were done using thin, sapphire impactors in order to measure the release of the shock wave in the QP specimens. (Specifications for these release shots are given in Table 2.) A compilation of the results of these experiments is shown in Figure 8 for the gas gun shots and Figure 9 for the powder gun shots. In addition, the release states can also be determined from shots done on the gas gun where the primary interest was Hugoniot data. A compilation of the results from these shots is given in Figure 7. These data have not been analyzed to date to obtain the release wave speeds or the release stress-strain states for the material.

Discussion

Hugoniot Relationship for QP

The Hugoniot relationship developed in this study has a C_0 of 2.62 mm/ μ s and S of 1.90. This data is compared in Figure 14 with that determined by Munson for 2D quartz phenolic with the same initial density and presumably with a similar weave and manufacturing process. Munson's data can be viewed from two different perspectives. First, taking the averaged values for C_0 and S for a particle velocity from 0 to 2 mm/ μ s gives his reported values of 3.15 mm/ μ s and 1.06, respectively. They appear different than the currently reported values from this study. However, a second approach is to look at the details of Munson's experiments. In this approach, two different Hugoniot relationships were fit depending upon the type of gauge used. The data taken with quartz gauges in the particle velocity regime of 0 to 0.4 mm/ μ s gave a curve fit corresponding to a C_0 of 3.09 mm/ μ s and an S of 1.89. The shift in C_0 between Munson's data and this study could be caused by a subtle difference in the two materials. More importantly, the close match of the two slopes or S values, strongly suggests a similar shock response of the two materials. The quite different values for C_0 and S for Munson's data derived from manganin gauge measurements as compared to his quartz gauge data or data from this study probably simply reflects the inaccuracy of manganin gauges in this shock regime during that time domain.

Attenuation within QP

Although only a few attenuation experiments were performed, the results do give a trend for attenuation in this material. As little as 7 mm of material causes the shock to attenuate in half.

Spall Strength of QP

From the data taken from the spall strength experiment and shown in Figure 10, a spall strength of 0.077 GPa was calculated. This value correlates with the spall strength of non-filled phenolic and suggests that the fracture took place between layers of the quartz weave in the matrix of phenolic. An agreement with this suggestion was work done in the '70's by Barker et. al.[10] on some quartz phenolic hardware. After an impact test using an aluminum flyer plate unto a quartz

phenolic-beryllium ring, they observed that the spall occurred between the first and second quartz weaves and within the phenolic matrix. They also calculated that the minimum tensile stress which caused the spall was 0.10 GPa, a close agreement with the presently measured value of 0.077.

Shock Release States

In the Results section of this report, a summarization was given for the three groupings of experiments from which shock release data can be obtained. These experiments were, first, thin impactors onto QPs using the light gas gun, second, thin impactors onto QP using the powder gun with both measuring transmitted shock waves, and, third, Hugoniot shots on the light gas gun using thin impactors of QP onto standard material targets such as PMMA, fused silica, LiF and sapphire. Further data analysis is necessary to determine the stress-strain states in this release information.

Table 3 also tabulates the particle velocity measured at the QP-target/PMMA-window for the gas gun and powder gun shock release shots, respectively. Knowing the Hugoniot relationships for the PMMA-window and the sapphire-impactor materials and by measuring the projectile velocity, the expected particle velocity in the PMMA-window material can be calculated. Table 3 shows that the measured values are consistently lower than the predicted values. In addition, examining the particle velocity profiles of Figures 8 and 9 for the gas gun and powder gun shock release shots, respectively, it is noticed that the "equilibrium" particle velocity for a given shot continues to increase in value until the drop due to the release of the shock wave. One possible explanation of these observations is that some residual porosity within the phenolic laminate is being squeezed out by the impact pressure but is not yet complete when the release wave arrives. This idea is further substantiated by comparing particle velocity profiles by length of pulse width. The longer the pulse width, the more time to squeeze out porosity, the more time to approach theoretical density, the closer the measured value of particle velocity is to that predicted from the Hugoniot relationship. However, other explanations such as rate effects may play a role in these observations. Further work would be needed to clarify these results.

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TABLE 1
Results of Ultrasonic Sound Measurements

Specimen	Longitudinal Velocity (mm/ μ s)	Shear Velocity (mm/ μ s)
1	3.467	1.941
2	3.477	1.930
3	3.459	1.915
4	3.477	1.928
5	3.480	1.918
6	3.470	1.913
7	3.452	1.900
8	3.482	1.933
9	3.503	1.933
10	3.480	1.913
11	3.449	1.877
12	3.449	1.900
13	3.475	1.943
14	3.485	1.956
15	3.459	1.897
16	3.470	1.951

TABLE 2
Specifications for Gun Shots

Shot Number	Impactor/ Backing Thickness (mm)	Impactor/ Backing Material	Target or Buffer Thickness (mm)	Target or Buffer Material	Window Thickness (mm)	Window Material	Projectile Velocity (mm/ μ s)	Particle Velocity in Window (mm/ μ s)
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Hugoniot Shots on Gas Gun

462	3/ 6.35	QP/ Carbon Foam	1	PMMA	12.7	PMMA	1.398	0.83
461	4/ 6.35	QP/ Carbon Foam	1	Fused Silica	12.7	Fused Silica	1.392	0.53
485	3/ 6.35	QP/ Carbon Foam	1	Sapphire	25.4	Sapphire	1.405	0.215
504	3/ 6.35	QP/ Carbon Foam	0	None	25.4	Sapphire	1.408	0.216

Attenuation Shots on Gas Gun

416	1/ 6.35	Sapphire/ Carbon Foam	7	QP	0	None	1.171	1.14*
420	1/ 6.35	Sapphire/ Carbon Foam	4	QP	12.7	PMMA	1.162	0.75

Spall Shot on Gas Gun

419	6.35/ 6.35	Sapphire/ Carbon Foam	7	QP	0	None	0.190	0.33*
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TABLE 2 (cont'd)**Release Shots on Gas Gun**

412	6.35/ 6.35	Sapphire/ Carbon Foam	7	QP	12.7	PMMA	0.485	0.49
413	6.35/ 6.35	Sapphire/ Carbon Foam	7	QP	12.7	PMMA	0.847	0.82
414	6.35/ 6.35	Sapphire/ Carbon Foam	7	QP	12.7	PMMA	1.171	1.10
422	6.35/ 6.35	Sapphire/ Carbon Foam	7	QP	12.7	PMMA	1.303	1.24

Release Shots on Powder Gun

11	6.35/ 6.35	Sapphire/ Carbon Foam	4	QP	12.7	PMMA	1.358	1.28
12	6.35/ 6.35	Sapphire	4	QP	12.7	PMMA	1.860	1.71

*free-surface velocity, U_f

TABLE 3
Calculated Values from Gun Shots

Hugoniot Shots on Gas Gun

Shot Number	Particle Velocity in QP (mm/μs)	Shock Velocity in QP (mm/μs)	Pressure (GPa)
462	0.578	3.76	3.73
461	0.862	4.14	6.09
485	1.190	4.85	9.87
504	1.192	4.86	9.91

Release Shots on Gas Gun

Shot Number	Particle Velocity Measured in PMMA (mm/μs)	Particle Velocity Predicted in PMMA (mm/μs)
412	0.49	0.50
413	0.82	0.86
414	1.10	1.17
422	1.24	1.29

Release Shots on Powder Gun

11	1.28	1.34
12	1.71	1.79

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Figure 1

HUGONIOT

Figure 2

RELEASE

Figure 3

ATTENUATION

Figure 4

SPALL

Figure 5

HUGONIOT / RELEASE POWDER GUN

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

END

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