

Shock Compression of Teflon from 2.5 to 25 kbar—Evidence for a Shock-Induced Transition*

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(Received 8 April 1971)

50-R-71

CHAM-AR 71-1126

Uniaxial shock-compression studies were conducted on Teflon in the stress region between 2.5 and 25 kbar using a compressed-gas gun and quartz-gauge instrumentation. Measurements of stress and particle velocity at the impact surface show that a transition occurs at 5.0 ± 0.2 kbar with an associated volume change of approximately $2.2 \pm 0.2\%$. Measurements of the stress wave profiles after transmission through the samples show an attenuation of peak stresses and suggest a viscoelastic behavior of Teflon.

I. INTRODUCTION

At room temperature, Teflon¹ undergoes a pressure-induced phase transition at a hydrostatic pressure of 5.4 ± 0.1 kbar^{2,3} with an associated volume change of approximately 2.3%.^{3,4} X-ray studies have shown that below the transition, the polytetrafluoroethylene molecules are in a helical conformation with a 180° twist occurring every 13 CF_2 units along the polymer chain.⁵ Above the transition, the molecules are in a more closely packed arrangement, and it has been suggested that the molecules may be more tightly twisted with a 180° twist every 9 CF_2 units along the polymer chain.⁶ A relatively large amount of shock-compression data is available for Teflon at high pressures,⁷ but little data is available below 30 kbar, and shock-compression experiments have not been reported in the vicinity of this transition. It is of interest to compare shock-transition and static-transition pressure measurements,⁸ particularly since a comparison has not previously been made on polymeric solids. It is the purpose of this paper to report the results of shock-compression measurements on Teflon from 2.5 to 25 kbar which were undertaken to investigate the possibility of a shock-induced phase transition.

Shock compression was accomplished by impact of a projectile from a compressed-gas gun, and the required experimental data were obtained by the front-back quartz-gauge technique^{9,10} in which the impact stress is measured directly by a quartz gauge mounted in the projectile, and the transmitted stress profile is measured by another quartz gauge mounted behind the target specimen. In Secs. II–IV the experimental technique will be described briefly and the experimental results will be presented and discussed.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

Shock-compression experiments were carried out on a 2.5-in.-diam compressed-gas gun. The gun is the one described in Ref. 9, with several improvements made to the system. The RG/9 coaxial cables have been replaced with foam-dielectric and air-dielectric

cables, and Tektronix 454 and 585 oscilloscopes are now used. Compressed helium as well as compressed air can be used so that the velocity capability of the gun has been extended to approximately 0.65 mm/ μsec . Angular misalignment, or tilt between the projectile and target surfaces is typically controlled to less than 600 μrad .

The front-back quartz-gauge technique has been described in detail in Refs. 9 and 10 and, therefore, will be discussed only briefly here. The experimental configuration is shown in Fig. 1. A Teflon disk with a 1.25 in. diam and 0.05–0.375 in. thick is mounted in a target cup at the end of the evacuated gun barrel and is impacted by a flat-faced projectile. The projectile velocity is measured to an accuracy of $\pm 0.5\%$. The target specimen has a quartz gauge in contact with its rear surface, and the projectile has a quartz gauge embedded in its face. The projectile gauge measures the stress at the impact surface, or front, of the sample, and the back gauge measures the transmitted stress profile. The electrical signals from the two gauges are recorded on separate oscilloscopes. The two signals are also recorded on a dual-beam oscilloscope, and the difference in start times of the two signals is taken as the shock transit time through the sample from which the average shock velocity is computed. With this method the accuracy of the shock-velocity measurement is $\pm 1.5\%$.

The front gauge records are analyzed in the following way: The stress jump at the impact surface σ_{impact} is calculated directly from the piezoelectric response of the gauge.¹¹ The particle velocity in the quartz gauge u_q is then calculated from the relation

$$u_q = \sigma_{\text{impact}} / \rho_q U_q, \quad (1)$$

where ρ_q and U_q are the known density and shock velocity of quartz,¹¹ respectively. If one then assumes continuity of mass across the impact surface, the particle velocity in the sample u_s is given by

$$u_s = U_0 - u_q, \quad (2)$$

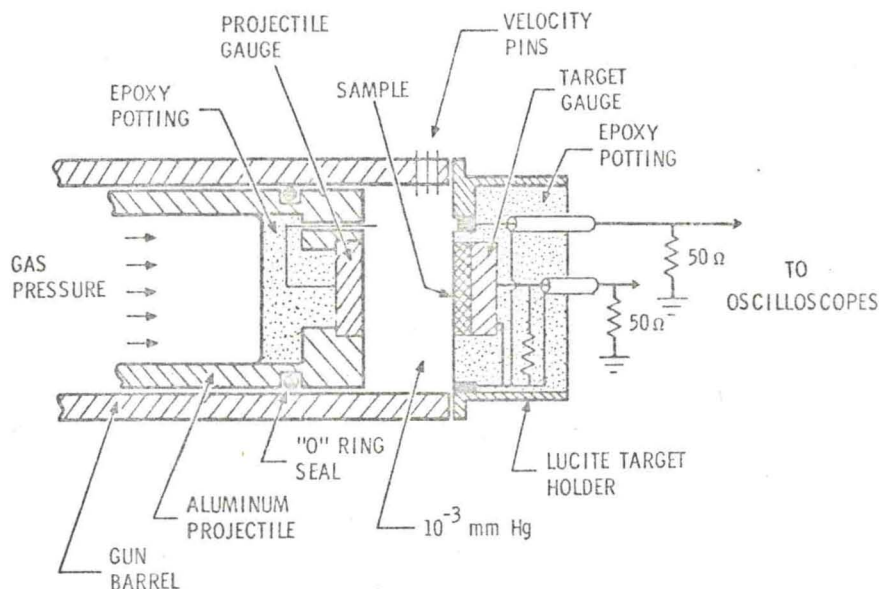


FIG. 1. Experimental assembly for measuring impact and transmitted stress-time profiles. The impact is accomplished with a projectile-mounted quartz gauge which measures the impact-surface stress-particle-velocity response of the sample. After the stress wave traverses the Teflon sample, the back surface gauge records the interface stress-time profile. The difference in start times of the gauge signals provides a measure of shock-wave velocity.

where U_0 is the measured projectile velocity. In this manner one obtains the impact Hugoniot of the sample in the σ, u plane. The measured impact stress and particle-velocity values are estimated to be accurate to 3% and 1%, respectively. If one also assumes that the stress at the impact surface is propagated into the specimen with a steady profile, the associated volume change can be calculated from the relation

$$(V_1 - V_2)/V_1 = \rho_1(u_2 - u_1)^2/(\sigma_2 - \sigma_1) \quad (3)$$

where V is the specific volume of the material, and the subscripts 1 and 2 refer to conditions ahead of and behind the shock front, respectively.

The stress-measured by the back gauge is the interface stress produced when the shock wave propagating in the sample interacts with the sample-quartz interface. To interpret the data, an acoustic mismatch calculation must be accomplished to obtain the incident stress in the sample which corresponds to the stress measured in the gauge. For a material whose Hugoniot in the stress-particle velocity plane has considerable curvature, the usual linear mismatch relation cannot be used. One possible procedure for carrying out the calculation is that suggested by Halpin and Graham¹² and is illustrated in Fig. 2. The Hugoniot of the sample is first assumed to be a least-squares fit to the σ, u data obtained from the impact-surface measurements described above. A computer program is then used to calculate a reflection of this curve which intersects the quartz Hugoniot at a point measured by the back gauge (point 1). This reflection intersects the impact Hugoniot at point 2. A straight line drawn from the origin with slope $\rho_0 U_s$ will intersect the reflected Hugoniot at point 3 and the impact Hugoniot at point 4. If points 2, 3, and 4 coincide, the assumed

Hugoniot is verified as correct for the transmitted wave profile. If the intersections do not coincide, an iterative procedure, in which successively different curves are assumed for the specimen Hugoniot, can be used until convergence is obtained.

III. RESULTS AND DISCUSSION

Figure 3 shows a typical pair of quartz-gauge records for an impact stress of 6.6 kbar. Figure 3(a) is the projectile gauge record and 3(b) is the back gauge record (time increases from left to right).

A summary of the experimental data is given in Table I. In studying Table I, it should be emphasized that each experiment accomplishes three independent measurements of material response. The relation of impact-surface stress and particle-velocity is obtained independently of the shock velocity and rear-surface stress amplitude measurements. Figure 4 shows the data from the impact-surface measure-

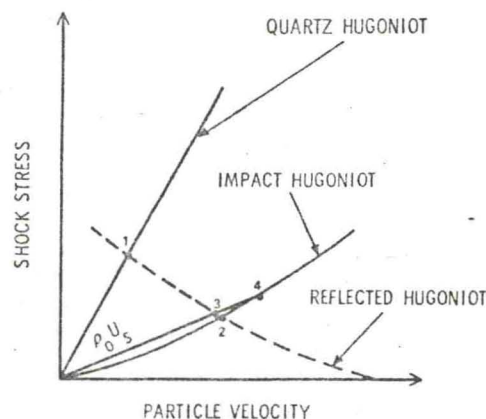


FIG. 2. Graphical illustration of the analysis of back-surface quartz gauge records. The analytical method depicted is undertaken to determine the incident stress amplitude from the quartz gauge signal.

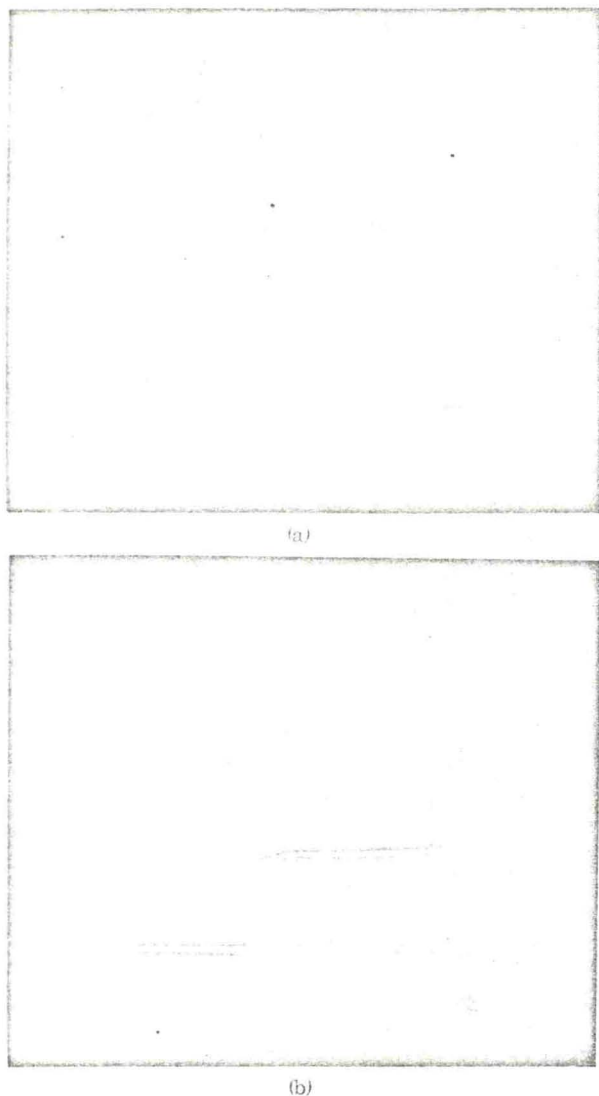


FIG. 3. Typical front and back quartz gauge current-vs-time records. Impact stress is 6.6 kbar while back-surface stress in the gauge is 10.8 kbar. (a) Shows the front gauge record and (b) shows the back gauge record. Time increases from left to right. Timing waves are 25 MHz.

ments. The discontinuity which initiates at 5.0 ± 0.2 kbar is believed to be the phase transition which has been observed at 5.4 kbar hydrostatically.^{2,3} Above the transition region, the data point of Anderson and Fahrenback¹³ at 17.6 kbar is in good agreement with our data, and a parabolic fit to our data between 6.3 and 24.2 kbar by the method of least squares extrapolates into good agreement with their data point at 33.5 kbar. Below the transition region, the data can be represented by the relation $\sigma = 31.04u + 39.01u^2$, and above the transition, the data can be represented by $\sigma = 26.10u + 55.99u^2$ (σ in kbar, u in mm/ μ sec). In Fig. 5, a plot of the measured shock velocity vs the particle velocity measured at the impact surface also shows a discontinuity. The point at $u=0$ is the longitudinal sound speed of 1.40 mm/ μ sec measured by Asay *et al.*¹⁴ for Teflon. Below and above the transition, least-squares fits to the data give

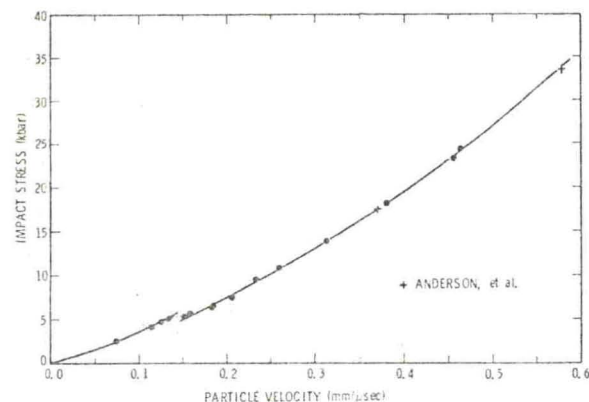


FIG. 4. Shock stress-vs-particle velocity for Teflon as determined from impact-surface measurements. The phase transition is indicated by the change in slope beginning at 5 kbar.

$$U = 1.393 + 2.217u \text{ and } U = 1.258 + 2.434u, \text{ respectively.}$$

Figure 6 shows impact stress vs compression $\Delta V/V_0$ calculated from Eq. (3). For stresses below the transition or far enough above the transition that it is overdriven,¹⁵ V_1 and ρ_1 in Eq. (3) are the specific volume and the density of the material at atmospheric pressure, and σ_1 and u_1 are equal to zero. Before the transition is overdriven, V_1 , ρ_1 , σ_1 and u_1 are the values associated with the transition. From the impact data of Fig. 4, a well-defined transition stress cannot be obtained; one can only conclude that the transition appears to begin somewhat above the data point at 4.8 kbar and below 5.3 kbar. The back-surface measurements also do not yield a well-defined transition stress. Therefore, for the purpose of converting the measured data of stress-vs-particle velocity to the stress-vs-volume plane, a transition stress of 5.0 kbar was assumed with the corresponding values of $u = 0.137$ mm/ μ sec and $\Delta V/V_0 = 0.0816$. It was further assumed that the critical transition stress is independent of applied shock stress. A straight line drawn from the origin to the point $\sigma = 5.0$ kbar, $u = 0.137$ mm/ μ sec inter-

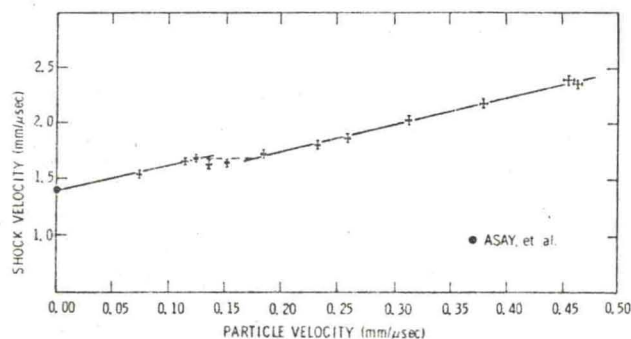


FIG. 5. Measured shock velocity-vs-particle velocity for Teflon. The point at zero particle is from the ultrasonic measurements of Asay *et al.* (Ref. 14).

TABLE I. Shock-compression data Teflon, $\rho_0 = 2.175 \text{ gm/cm}^3$.

Impact-surface measurement				Transmitted profile			
^a σ_{impact} (kbar)	^b u_p (mm/ μsec)	^c $\Delta V/V_0$	Sample thickness (mm)	^d U_s (mm/ μsec)	^e σ_q (kbar)	^f σ_s (kbar)	Attenuation (%)
2.5	0.074	0.048	6.965	1.54	3.95	2.28	8.8
4.1	0.116	0.072	5.080	1.64	6.5	...	...
4.6	0.125	0.073	7.277	1.69	7.4	...	...
4.8	0.135	0.082	5.085	1.63	8.2	...	...
5.3	0.152	0.096	5.151	1.65	8.9	...	...
5.6	0.158	0.097	4.925	...	9.3	...	...
6.4	0.183	0.116	1.290	...	11.4	6.2	3.1
6.6	0.184	0.113	4.839	1.73	10.8	6.0	8.5
7.5	0.207	0.124	4.935	...	...	...	...
9.5	0.233	0.125	5.177	1.81	14.9	8.2	12.8
10.8	0.260	0.136	5.187	1.87	16.8	9.4	13.4
13.8	0.313	0.154	9.550	2.03	...	...	...
18.0	0.380	0.174	8.641	2.19	...	...	...
23.2 ^g	0.456	0.195	5.133	2.40	...	...	...
24.3 ^g	0.463	0.192	5.105	2.36	...	...	...

^aFrom projectile gauge measurement.^bCalculated from Eqs. (1) and (2).^cCalculated from Eq. (3) using impact data.^dFrom transit time measured from the difference in start

times of front and back gauge records.

^ePeak stress in back quartz gauge.^fPeak stress in sample computed by the method of Fig. 2.^gProjectile gauge faced with sapphire (Ref. 19).

sects the curve at 7.5 kbar. The transition is assumed to be overdriven above this stress. The solid lines in Fig. 6 are parabolic least-squares fits to the data above and below the transition region. The results indicate a volume change of $2.2 \pm 0.2\%$ in going through the transition. A volume change of approximately 2.3% was observed hydrostatically.^{3,4}

The transmitted wave profiles suggest a viscoelastic behavior. The stress-time histories are qualitatively similar to those observed in polymethylmethacrylate¹⁶ in that they show an initial rapid increase in stress followed by a more gradual approach to a maximum stress. A wave analysis based on theories of viscoelasticity¹⁷ is beyond the scope of this paper.

Even though a phase transition would ordinarily cause a multiple wave front in the transmitted stress profile,¹⁵ experiments just above the transition stress do not show a two-wave structure [see Fig. 3(b)]. The rather small volume change associated with the transition, the fact that under hydrostatic pressure the transition requires approximately 15 min to go to completion at room temperature,¹⁸ and the observation that the mixed-phase region is only approximately 2.5 kbar wide lead one to conclude that a two-wave structure is obscured by viscoelastic or other time-dependent effects.

The transmitted profiles indicate some attenuation of the peak shock stress as the wave propagates through the specimen. In Table I, the peak stress from the back gauge is shown. For these stresses in the quartz, the peak stress in the Teflon samples was calculated by the procedure of Fig. 2 for the experiment at 2.5-kbar impact stress and for experiments above the transition region. These values are also shown in Table I. For samples 0.2 in.

thick, the attenuation increased from 8.5% at 6.5 kbar to 13.4% at 10.8 kbar. At 6.5 kbar the attenuation varied from 3.1% to 8.5% for samples 0.051–0.20 in. thick, respectively.

IV. CONCLUSIONS

Impact experiments on Teflon indicate that a transition takes place at 5.0 ± 0.2 kbar. This is believed to be the same structural transition which has been observed under hydrostatic pressure at 5.4 ± 0.1 kbar. In hydrostatic experiments, the transition pressure was observed to decrease slightly with increasing temperature. Therefore, it is reasonable that our value should be lower than the hydrostatic value because of shock heating. The volume change of $2.2 \pm 0.2\%$ which we observe is in good agreement with the volume change of 2.3% observed hydrostatically. Transmitted shock-wave profiles suggest a

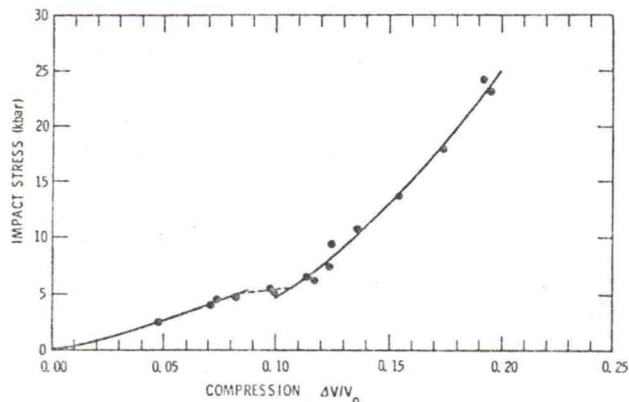


FIG. 6. Shock stress-vs-compression for Teflon calculated from impact-surface measurements. The volume change of $2.2 \pm 0.2\%$ is in good agreement with that observed hydrostatically (Refs. 3 and 4).

viscoelastic behavior for Teflon and show an attenuation in peak shock stress as a wave propagates through a sample.

V. ACKNOWLEDGMENT

The author gratefully acknowledges the technical assistance of G. T. Holman in constructing and carrying out these experiments.

*Work Supported by the U.S. Atomic Energy Commission.

¹Polytetrafluoroethylene—trade mark, E.I. duPont de Nemours Co.

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¹⁸The observation that a transition which is slow under hydrostatic pressure can occur on the microsecond time scale of a shock experiment is not unusual. The high shear stresses which occur in the shock front and the temperature rise associated with shock experiments are believed to be responsible for the faster transition mechanism under shock loading. See, for example, B. J. Alder, in *Solids Under Pressure*, edited by W. Paul and D. M. Warschauer (McGraw-Hill, New York, 1963), p. 385.

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