THE TAYLOR IMPACT RESPONSE OF PTFE (TEFLON)

Philip J. Rae*, George T. Gray III*, Dana M. Dattelbaum† and Neil K. Bourne**

**MST-8, MS-G755, LANL, Los Alamos, NM 87545*
†MST-7, MS-E549, LANL, Los Alamos, NM 87545
***Cranfield University, Defence Academy of the United Kingdom, Shrivenham, Swindon, SN6 8LA, U.K.*

Abstract. Whilst Polytetrafluoroethylene (PTFE) is an unusually ductile polymer, it undergoes an abrupt ductile-brittle transition at modest impact velocities. No previous explanation for this behaviour seems to have been presented. In this paper we examine the role of a pressure-induced phase transition in PTFE in the failure of Taylor cylinder samples. Whilst a phase transition occurs at approximately 0.65 GPa at 21°C, the transition pressure is inversely related to temperature. Varying the temperature of the fired Taylor cylinders shows that the phase transition is likely to be involved because the critical velocity increased for decreasing temperature, despite the material fracture toughness decreasing.
Keywords: Polytetrafluoroethylene, PTFE, Taylor Impact
PACS: 43.35.Ei, 78.60.Mq

INTRODUCTION

Although P.T.F.E (polytetrafluoroethylene) is a commonly used material in industry and engineering, its mechanical response has received relatively little study in recent years. Early literature on PTFE describes a ductile, inert and stable polymer[1, 2], that had many potential uses in bearings, gaskets and electrical fittings. PTFE is unique among polymers in retaining some measure of ductility (≈3-5 %) at liquid helium temperatures. It was therefore surprising that such a ductile polymer should undergo an abrupt ductile–brittle transition when impact loaded at quite modest rates. The earliest report of this transition occurred in 1958 in a report prepared by the University of Texas for the Sandia Corporation[3]. PTFE samples of various geometries were impacted by a 830 g projectile at 58 m s^{-1}. In most impact experiments the samples disintegrated into small pieces, whilst at quasi-static loading rates, the same geometries deformed gracefully in a ductile manner. Previous authors have commented on the sometimes ‘brittle’ nature of PTFE, but to our knowledge, no explanation has been postulated.

A small team at Los Alamos National Laboratory has been tasked with investigating the properties of PTFE with a view to developing a realistic constitutive model of the polymers behaviour over a wide range of strain-rates, stress-states and temperatures. As part of this study, Taylor cylinder[4] experiments were conducted, together with high-speed photography to observe the ballistic behaviour of PTFE. It was quickly realised that the ductile–brittle transition reported in the literature was exhibited in the Taylor test and an explanation for this response was sought.

MATERIAL

Central to the goal of developing a mechanical material model for PTFE was the use of pedigreed polymer material. Too many mechanical response papers, particularly in the field of polymers, relate that a sample of ‘α’ was tested with no further mention of exact chemistry, how it was processed, what its morphology was or how it was aged, appearing in the report. For this study a single $600 \times 600 \times 65$ mm^3 billet of DuPont 7A Teflon was sintered from a

TABLE 1. Properties of the Teflon 7A tested. See Lehnert[5] for information on the different methods of estimating PTFE crystallinity.

Property	Value
Density (Immersion)	2.1583 kg m^{-3}
Density (Pycnometry)	2.1577 kg m^{-3}
Crystallinity (X-Ray Diffraction)	69%
Crystallinity (Density)	43%
Crystallinty (MDSC)	32%
Crystallinty (Infra-red)	73%

known powder batch, to a known pressing and heating schedule. Samples of the billet were cut to confirm the isotropic nature of the billet and various other physical properties were quantified, see Table 1 for details. The Taylor cylinders machined for these experiments were taken from the through-thickness (65 mm) direction of the billet.

PTFE is a complex material. It exhibits at least four phase changes depending on a combination of temperature and pressure[6]. Additionally, PTFE always contains a mix of amorphous and crystalline regions, it is not possible to manufacture fully amorphous or fully crystalline PTFE. At atmospheric pressure, below 19°C, PTFE has a triclinic crystalline structure (II). Above this temperature it undergoes a 1st order phase transition into a hexagonal structure exhibiting a 1.8% volume increase (IV). A second order transition occurs at 30°C into pseudo-hexagonal (I). From 30°C until melting (321°C for once melted material, 341°C for virgin moulding powder) a general relaxation of the crystalline structure occurs until, given enough time, a fully amorphous state is reached.

A pseudo-equilibrium pressure-induced phase transition has been reported in PTFE at ≈0.65 GPa at room temperature (III) [7, 8]. This transition is strongly temperature dependent, as shown in Figure 1, however considerable hysterisis was noted leading to large error bars. Recent work at Los Alamos using a diamond cell anvil and Raman Spectroscopy suggests the transition occurs at 0.65 GPa and exhibits around ±0.5 GPa of hysterisis.

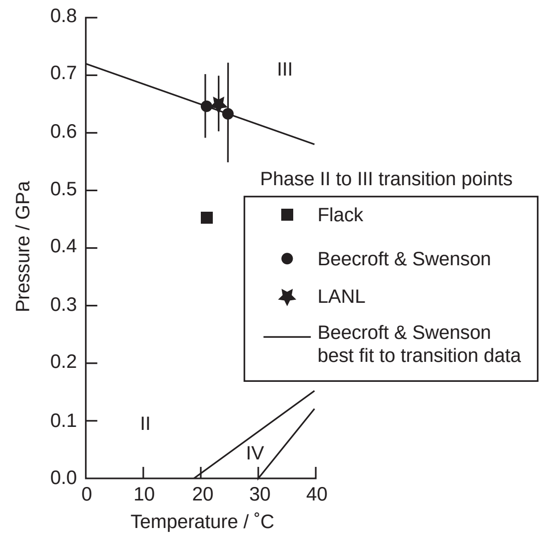

FIGURE 1. The strongly temperature related nature of the pressure-induced phase transition in PTFE.

EXPERIMENTAL

A helium gas driven gun was used for these Taylor experiments[4]. 50.8 mm (2 inch) long right-cylinders were fired at a 91 kg hardened steel anvil. The impact face of the anvil is polished to a mirror finish and the surface lubricated with a synthetic oil containing colloidal PTFE. The sample is fired into an evacuated catcher chamber.

A three inch section of the barrel at the breech end is capable of being heated or cooled between +200 and -100°C using electrical heaters or liquid nitrogen cooling coils. In this way the impact behaviour of samples may be investigated with respect to temperature. For these PTFE tests, samples were heated or cooled to the desired temperature for at least one hour in an environmental chamber before being quickly loaded in to the temperature controlled section of the Taylor barrel.

Owing to the soft nature of PTFE and the low velocities used (120-150 m s^{-1}) the anvil remained well within the elastic regime and no visible damage to the impact face was caused. An Imacon 200 high-speed camera was used to photograph the shots. This camera is capable of taking up to 16 frames at a maximum rate corresponding to 200 million frames per second. The exposure time and inter-frame time (IFT) of each exposure are fully programmable. In

TABLE 2. Measured ductile-brittle transition velocities vs. temperature.

Temperature / °C	Transition Velocity / m s^{-1}
1	139±2
21	134±1
40	131±1

these experiments 14 frames were used with a 500 ns exposure and a 15 μs IFT. The projectile velocity was measured using two laser beams spaced 32.28 mm apart.

RESULTS

Taylor samples were found to exhibit an abrupt ductile-brittle transition. Figure 1 shows the marked change in response for only a 1 m s^{-1} change in velocity at 21°C. Figure 1 shows the fracture threshold map plotted for 7A Teflon at 21°C. It was decided to see if the pressure-induced phase transition in PTFE might play a part in this behaviour.

A primitive dynamic finite element model (elastic, perfectly plastic) of a Taylor impact was run using the Lagrangian EPIC code[9]. An axisymmetric PTFE rod was simulated impacting an infinite smooth steel block at 135 m s^{-1}. A maximum compressive hydrostatic stress of $\approx$0.5 GPa was generated approximately 3 μs after impact. At later times, tensile stresses develop in the end of the rod. From this it was concluded that the magnitude of the stress was of the correct order to affect the material. Further shots were carried out to test this hypothesis making use of the strongly temperature sensitive nature of the phase transition.

The mechanical response of a polymer is affected by temperature. Generally, lowering the temperature increases the yield strength, but lowers the fracture toughness. This is the case with PTFE. Figure 1 shows the effect of temperature on the compressive properties of 7A Teflon whilst Figure 1 shows the fracture toughness (Gc) verses temperature. To limit the effect of mechanical property changes, additional Taylor shots at 1 and 40°C were undertaken. Table 1 shows the measured ductile-brittle transition velocity with respect to temperature.

DISCUSSION

Definitive evidence of a phase transition during impact is difficult to obtain because flash X-Ray crystallography would be required. Post sample analysis is likely to be inconclusive because the phase transition is known to be reversible upon unloading. The ductile-brittle transition is certainly abrupt enough to be related to a phase transition. Given that the critical velocity of the Teflon 7A actually increased with lower temperature is further evidence because, as reported, the fracture toughness of Teflon would be decreased at temperatures higher and lower than the 19°C phase transition. Whilst the strength of Teflon is increased at lower temperatures, the strain-to-failure is reduced[10].

Further evidence that the variability in strength of the PTFE with temperature is not playing a part can be derived from high-speed photography. Samples that are going to fail in a brittle manner do so within the first 15 μs, and at radial strains smaller than those supported at later times in specimens that do not become brittle. It will be remembered from the computer model that the maximum hydrostatic stress was developed approximately 3 μs after impact. Similar room temperature Taylor experiments under take at Cranfield University on un-pedigreed extruded PTFE material show a similar failure transition velocity to that found in Teflon 7A. It may therefore be supposed that the material processing does not, to a first order, effect the impact fracture behaviour. This would be consistent with a phase transition phenomena being involved.

In conclusion, it is felt that these Taylor shots present strong evidence in favour of a pressure-induced phase transition being responsible for the ductile-brittle transition found in PTFE.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support for this research from the joint DOD/DOE MOU on the dynamic behaviour of polymers.

REFERENCES

1. Renfrew, M. M., and Lewis, E. E., *Industrial and Engineering Chemistry*, **38**, 870–877 (1946).

2. Sperati, C. A., and Starkweather, H. W., *Advances in Polymer Science*, **2**, 465–495 (1961).
3. Ripperger, E. A., Stress-strain characteristics of materials at high strain rates, part ii, Tech. Rep. AT(29-2)-621, Structural Mechanics Research Laboratory, UT (1958).
4. Maudlin, P. J., Bingert, J. F., and Gray III, G. T., *International Journal of Plasticity*, **19**, 483–515 (2003).
5. Lehnert, R. J., Hendra, P. J., Everall, N., and Clayden, N. J., *Polymer*, **38**, 1521–1535 (1997).
6. Weir, C. E., *Journal of Research of the National Bureau of Standards*, **50**, 95–97 (1953).
7. Beecroft, R. I., and Swenson, C. A., *Journal of Applied Physics*, **30**, 1793–1798 (1959).
8. Flack, H. D., *Journal of Polymer Science: Part A-2*, **10**, 1799–1809 (1972).
9. Johnson, G. R., Stryk, R. A., Holmquist, T. J., and Beissel, S. R., User instructions for the 1997 version of the epic code., Tech. Rep. WL-TR-1997-7037, Wright Laboratory, Armament Directorate, Eglin Airforce Base (1997).
10. Koo, G. P., *Cold drawing behaviour of Polytetrafluoroethylene*, Ph.D. thesis (1969).