

THE MECHANICAL AND OPTICAL RESPONSE OF POLYCHLOROTRIFLUOROETHYLENE TO ONE DIMENSIONAL SHOCK LOADING

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A series of plate impact experiments have been performed to probe the shock behaviour of polychlorotrifluoroethylene (PCTFE), in terms of its optical and mechanical response. Interfacial velocity measurements using interferometric techniques have shown differences between measured and actual velocities, and been used to determine changes in refractive index due to shock induced density increases. These have further been used to determine an optical correction factor, and allows the possibility of PCTFE being used as an optical window in future shock loading experiments. The shear strength of shock loaded PCTFE has also been shown to be near constant behind the shock front, in common with other fluorinated polymers, although the strength variation with impact stress is greater than other similar materials. It has been suggested that the presence of a larger chlorine atom, replacing a fluorine allows for a degree of tacticity between polymer chains, with local

variations of charge density along the chain (due to the presence of the chlorine atom)
also having an effect.

I. INTRODUCTION

The use of polymers in high loading rate situations has a number of sources of interest. The most significant comes from the energetic materials community, where materials such as polyurethane rubbers (estane)^[1], Kel-F 800 (a copolymer of chlorotrifluoroethylene and vinylidene difluoride)^[2] and hydroxyterminated polybutadiene (HTPB)^[3] find application as the binder phases of plastic bonded explosives (PBXs). Polychloroprene has been used as a structural material in its own right for the protection of buildings from earthquakes^[4], whilst epoxy and phenolic resins are used as the matrix materials in fibre composites^[5, 6]. Finally, some polymers such as polyvinylidene difluoride (PVDF)^[7] can be conditioned such that they become piezoelectric in nature, and as such have found application as stress gages.

Fluorinated polymers find application in aggressive environments where conditions of pressure, temperature and strain-rate can be extreme. They are also noted for their resistance to chemical attack. The most common of this class of material is polytetrafluoroethylene (PTFE or the trade name Teflon), and to date has been studied most extensively under shock loading conditions. This material is a semi-crystalline polymer, with the chains adopting a number of crystalline domains around ambient pressures and temperatures. Of most relevance to shock loading experiments is the ambient temperature phase II to III transition at a pressure of 0.5 – 0.65 GPa. Phase II consists of a helical rotation of 13 CF₂ units, in a hexagonal array, giving way to a planar zig-zag conformation with the chains lying in either an orthorhombic or monoclinic lattice. Such behaviour has also been noted under shock loading conditions, for example Champion^[8] observed a change in the shock velocity (U_s) – particle velocity (u_p) corresponding to a pressure of *ca.* 0.5 GPa. Bourne and Gray^[9] made similar observations, drawing much the same conclusions. Nagao *et*

al.^[10] used a laser driven flyer plate to shock load PTFE to 1.0 GPa, using Raman spectroscopy to probe the response. Results showed that there was a stretching of the carbon-carbon bonds along with a twisting of the CF₂ groups, again suggesting the phase II to III transition. Rae *et al.*^[11] used Taylor impact experiments to study the high strain-rate response of PTFE. They showed that (at room temperature), PTFE underwent an abrupt change in response, showing a ductile response at an impact velocity of 133 m s⁻¹, and a brittle one at 134 m s⁻¹. Brown *et al.*^[12] performed one dimensional shock recovery experiments on PTFE, both above and below the II-III transition. Below the transition, results showed a decrease in crystallinity, Young's modulus and yield strength. Above it, increases in crystallinity, Young's modulus, yield strength and significant microstructural refinement were observed, indicating that a change in mechanical and microstructural response due to a phase transformation was occurring.

Although PTFE is an industrially important material, its properties are often modified by copolymerisation with other fluorinated monomer units, most often vinylidene difluoride (VDF; F₂C=CH₂) and hexafluoropropylene (HFP; F₃C-CF=CF₂). Eby and Wilson^[13] investigated the copolymerisation of TFE and HFP, demonstrating that PHFP had the highest modulus with a low temperature dependence, whilst PTFE had a much greater temperature dependence on modulus. All copolymers however, were more compliant than either 'pure' polymer. Further, their data indicated (although not commented upon) that the moduli changes observed between 19 and 30 °C in PTFE became ambiguous with additions of HFP as little as 3.4 wt%. This would suggest that the presence of a trifluoromethyl side group would act as a localised defect that would disrupt the ability of the polymer chain to crystallise. Plate impact experiments on copolymers of TFE, VDF and HFP showed

no evidence of a phase transition, in agreement with Eby and Wilson^[13]. Millett *et al.*^[14] showed that the Hugoniot of Viton-B (a copolymer of TFE, VDF and HFP) lay a little above that of PTFE, whilst Dattelbaum *et al.*^[15] indicated that the similar THV 500 whilst near identical to PTFE, was slightly lower than Viton-B, suggesting that differences in density may have an effect.

One fluorinated polymer of interest is polychlorotrifluoroethylene (PCTFE), marketed under the trade name Kel-F 81. This is a semi-crystalline polymer, similar to PTFE, but with a fluorine replaced by a chlorine atom. This has the effect of disrupting the close packing of polymer chains that is achievable with PTFE. The glass transition temperature (T_g) is higher in PCTFE at *ca.* 45 °C compared to PTFE (-73 °C). Conversely, the melting point in comparison to PTFE is lower (216 °C and 327 °C respectively). The shock response of PCTFE is comparatively sparse, with Hugoniot data reported by Marsh^[16], Carter and Marsh^[17] and Anderson^[2]. Brown *et al.*^[18] performed Taylor impact experiments, showing that in contrast to PTFE, where an abrupt transition from ductile to brittle was noted, the corresponding ductile to brittle transition occurred (at room temperature) up to a impact velocity of 34 m s⁻¹, reducing to 8 m s⁻¹ at 60 °C. It was suggested that these differences were due to the phase transformation in the PTFE enhancing fracture due to the reduction in volume. In contrast, in PCTFE, where no phase transition occurs, the change from ductile to brittle behaviour was more gradual.

II. EXPERIMENTAL

Two series of experiments were performed, looking at the shock induced equation of state and shear strength development respectively. The first series was performed using AWE's own in house plate impact facility, consisting of a 70 mm bore, 3 m

long, single stage gas launcher, using helium as the propellant. A 2 mm thick flyer plate was impacted onto a 5 mm target, both of which were made from PCTFE. Impact velocities were in the range 190 to 800 m s⁻¹. Each flyer was supported with a 3 mm disc of aluminium 5083-H32 to prevent flexing during acceleration along the barrel. The main reason for this series of experiments lay in a previous body of work^[19] to determine the release states in copper. This was achieved by mounting a series of varying impedance discs on the rear surface of a copper plate, monitoring the free surface velocities of those discs, and inferring the interfacial conditions from the known shock response of the various materials the discs were made from. One material chosen was PCTFE. In the subsequent analysis, it was observed that both the velocities at the free and impact surfaces could be observed. It was subsequently realised that if an optical correction factor for those velocities could be determined, it would thus be possible that PCTFE could be used as window material for future shock loading experiments. Interfacial velocities were measured at both the impact face and rear surface using a frequency shifted HetV (photonic Doppler velocimetry – PDV)^[20], with a 1550 nm class IV laser. Thin gold layers (*ca.* 100 nm) were sputter coated onto the relevant surfaces to improve the strength of the return signals. Impact velocities were measured using a non-shifted HetV system, mounted through a hole in the PCTFE target assembly. Diagnostics were triggered using a piezoelectric (lead zirconium titanate - PZT) pin (Dynasen CA-1136-2) mounted flush with the impact face. A schematic diagram of the target assembly is shown in figure 1.

FIGURE 1 NEAR HERE

The second series of experiments were performed on the 51 mm bore, 6 m long single stage gas launcher at Cranfield University^[21]. These were designed to probe the development of shear strength (τ) behind the shock front, both as a function of impact stress and time duration behind the shock front. This was done on the assumption that shear strength can be determined from knowledge of the longitudinal (σ_x) and lateral components of stress (σ_y), through the relation,

$$2\tau = \sigma_x - \sigma_y . \quad (1)$$

In practice, this can be done with suitably orientated manganin stress gages. Lateral stress was measured by sectioning in half a 10 mm thick, 60 mm diameter disc of PCTFE, and introducing a manganin stress gage (MicroMeasurements type J2M-SS-580SF-025) 2 mm from the front surface. The disc was then reassembled with a low viscosity epoxy resin, with 25 μm of mylar on either side of the gage as added protection. Voltage data from the gage were converted to lateral stress using the methods of Rosenberg *et al.*^[22], taking into account that the shape of the gage itself influences the response at low stress levels. After lapping the front surface of the reassembled target, a second manganin gage (MicroMeasurements type LM-SS-025CH-048) was supported on that surface with a 1 mm plate of either dural (aluminium alloy 6082-T6) or copper, matched to the material of the flyer plate. Gage data were reduced using the methods of Rosenberg *et al.*^[23] 10 mm flyer plates of either dural or copper were impacted at a velocity range of 368 to 529 m s^{-1} . A schematic diagram of the target assembly, along with a photograph showing that target assembly *in situ* within the gun is shown in figure 2.

FIGURE 2 NEAR HERE

III. MATERIALS

The material used in this study was purchased as a commercial, of the shelf product. Sound speed measurements were made via a pulse-echo method, using 5 MHz transducers in longitudinal and shear mode. The results are presented below in table I, along with the equivalent properties of PTFE as comparison.

TABLE I NEAR HERE

IV RESULTS.

In figure 3, we present representative results from HetV measurements on PCTFE, showing motion at the impact and rear surfaces. In this case, the impact conditions were 190.3 m s^{-1} . To aid interpretation, a schematic distance-time ($X-t$) diagram has been added in figure 4.

FIGURE 3 NEAR HERE

FIGURE 4 NEAR HERE

At the moment of impact, a shock wave will be launched into both the target (going right) and into the flyer (going left) at time a (velocity level i), reaching the rear surface of the target at time c , taking the material to a velocity level iii . The time

difference between a and c (shown as Δt in figure 2b) can be used to extract the shock velocity (U_S) from the known thickness of the target plate (w_0) via $U_S = w_0 / \Delta t$. The left travelling shock into the flyer will reach the higher impedance aluminium interface (time b), thus being reflected back as a reload. This reaches the impact face at time d , and the rear surface at time e , showing as a reload signal in the HetV measurements (velocity levels ii and iv respectively). The time difference between d and e (Δt_2) can be used to infer a second shock velocity (U_S^{2nd}), taking into account the material has now been shock compressed. This can be calculated via,

$$U_S^{2nd} = \frac{w_0}{\Delta t_2} \left(1 - \frac{u_p}{U_S} \right), \quad (2)$$

where u_p is the particle velocity (*i.e.* velocity of material flow) behind the first shock wave. However, it should be pointed out that the release from time c will interfere with the incoming second shock along bde , hence introducing an error into the final calculated shock velocity. We should further mention that due to the reflection of the second shock from the KelF-81 / aluminium alloy interface in the flyer, the material will be moving away from the principle Hugoniot to a more isentropic condition. This will introduce a further (small) error in these shock velocity measurements.

TABLE II NEAR HERE

An interesting feature emerges when we examine the *magnitude* of the velocities at the impact face and free surfaces (as summarised in table II). Given that the initial shock conditions are symmetrical (*i.e.* PCTFE flyer onto PCTFE target), one would

expect that the velocity at the impact face would be half that of the impact velocity, whilst that at the free surface would equal to impact velocity. In practice, both velocities are significantly *lower* than what would be expected. Firstly, consider the particle velocity at the impact face. The light returning from this point in the sample will be influenced by changes in the refractive index (n) of the material, hence the measured or apparent particle velocity (u_p^a) will be different from the particle velocity determined from the impact velocity. This is shown graphically in figure 5a. The linear relationship between the two (shown in the figure as ‘Linear Fit’) yields a value of 0.9881, which could be used as a simple optical correction factor (OCF).

FIGURE 5 NEAR HERE

However, Jensen *et al.*^[24] have pointed out that the variation of the refractive index for a single shock can be determined through comparison of the apparent and true particle velocities via the relation,

$$n = \frac{U_s n_0 - u_p^a}{U_s - u_p}, \quad (3)$$

where n_0 is the ambient refractive index. For PCTFE, this has been identified to be 1.425 at infrared wavelengths^[25]. To determine the optical correction factor, the variation of n with shocked density needs to be found. Density itself can be calculated through the conservation relations,

$$\rho = \frac{\rho_0 U_s}{U_s - u_p} . \quad (4)$$

Plotting refractive index against shocked density (figure 5b) gives a linear relationship of the form,

$$n = a(\lambda) + b(\lambda)\rho , \quad (5)$$

with $a(\lambda)$ and $b(\lambda)$ having values of 0.988 and 0.205 respectively. The zero density intercept, $a(\lambda)$ gives the window correction factor. It can be seen that this is near identical to the simple linear fit shown in figure 5a.

If we now consider the free surface velocities, in addition to the fact that they are lower than the impact velocity, they also have a pronounced rounded nature, in contrast to the initial shock at the impact face (time a) which is square. This implies that the mechanical properties of the PCTFE are modifying the shape of the shock pulse as it moves through the material, with some energy dispersive process, most likely yield reducing the overall amplitude somewhat. This also implies that the differences between twice the internal particle velocity and the free surface velocity should reduce as the ratio between the imposed longitudinal stress and Hugoniot Elastic Limit (yield strength under one dimensional strain) increase.

Representative gage traces from the shear strength experimental series are shown in figure 6. The impact conditions were a 10 mm dural flyer plate impacting at a velocity of 368 m s^{-1} . The primary purpose of these experiments was to determine the shear strength of PCTFE behind the shock front, through the differences in magnitude of the signal amplitudes, as shown in figure 6 and equation 1. As the longitudinal gage was

placed between the dural coverplate and the PCTFE target plate, its shape will be influenced by the passage of the shock front through *ca.* 1 mm of that material. As a consequence, the trace is relatively featureless, although the ultimate amplitude will give the longitudinal stress in the PCTFE. As the lateral gage is embedded within the body of the PCTFE itself, its response should yield more information concerning the behaviour of this material to shock loading. In this particular case, and in common with all the other shots in this series, the lateral stress trace was shown to possess a near flat response behind the shock front, suggesting that the variation of shear strength behind the shock front is near zero.

FIGURE 6 NEAR HERE

However, as the lateral gage was at a known position within the target assembly, and thus a known separation from the longitudinal stress gage (nominally 2 mm), it was also possible to make an estimation of the shock velocity. The results are presented in figure 7, along with the Hugoniot data gathered from the previous equation of state experiments made using HetV.

FIGURE 7 NEAR HERE

The equivalent data from Marsh for PCTFE^[16] has been included for comparison and confirmation. It can be seen that all three sets of experimental data from this paper agree with the existing data of Marsh^[16], with the HetV data taken from the first shock having the best agreement. The data from the second shock has a greater degree of uncertainty associated with it as it can be seen from figure 4, the release from the free

surface at time c will interfere with the oncoming shock (shown by line bde), resulting a reduction in velocity past the point of interaction. In the case of the points generated by gage measurements, the large errors are associated with the fact that only the nominal separation (2 mm) was known rather than actually measured. Even so, the calculated shock velocities are in reasonable agreement with both the previously published data, and our own more accurate HetV measurements. Note that the two higher particle velocity points, determined from stress gage positions, are significantly at odds with the other data sets. This is most likely due to errors in the estimated positions of the gages. The corresponding stress points shown in figure 7b in contrast are in closer agreement with the overall data distribution. The curve fit is according to,

$$P_{HD} = \rho_0 U_s u_p, \quad (6)$$

where P_{HD} is the hydrodynamic pressure and the relationship between U_s and u_s is assumed to be that quoted by Marsh^[16]. Note that agreement between the measured stress (from the gages) and the calculated hydrodynamic pressure diverges slightly at higher particle velocities. As the longitudinal stress is offset from the shock pressure (P) by the shear strength,

$$\sigma_x = P + \frac{4}{3} \tau, \quad (7)$$

This can be taken as a first indication that the shear strength in PCTFE increases with pressure, over the experimental range investigated in this report.

The shear strengths have been determined from the longitudinal and lateral stress traces using equation 1, and are presented as a function of impact stress in figure 8. As a comparison, the equivalent data for PTFE have been included^[26].

FIGURE 8 NEAR HERE

Note that both PCTFE and PVDF are significantly stronger than PTFE, indicating that modifying the surrounding atoms on the carbon backbone have a significant effect on strength. Results also suggest that at higher stresses, the greatest strength of all is shown by PCTFE.

Experimental conditions and results for this series of shots are summarised in table III.

TABLE III NEAR HERE

V DISCUSSION.

The shock response of PCTFE has been investigated in terms of its shock induced equation of state (the Hugoniot) and shock induced mechanical properties (mostly in terms of the variation of shear strength with shock amplitude and time). From figure 7, it can be seen that there is good agreement between the data generated in this investigation and the accepted data of Marsh^[16]. The two outlying shock velocity points (figure 7a) were generated using the assumed separation (2 mm) of the manganin stress gages in the lateral stress experiments. Thus any errors in gage placement will manifest as errors in the shock velocity. Note that the value of c_0 , at

$1.96 \text{ mm } \mu\text{s}^{-1}$ is significantly larger than the longitudinal sound speed ($1.74 \text{ mm } \mu\text{s}^{-1}$). In simple metals such as copper, c_0 generally equates with the bulk sound speed (c_B)^[16]. However, this is a purely empirical observation, and hence the differences observed in PCTFE suggest a more complex behaviour under shock loading. Such behaviour has been observed in other polymers, including polyethylene, polypropylene and polystyrene^[27], polyoxymethylene^[28], a silastomer^[29], epoxy resins^[5] and indeed the majority of polymers reported in the compendium of data presented by Carter and Marsh^[17]. It would suggest that the shock velocity – particle velocity relationship is non-linear at lower particle velocities. This has been observed in polymethylmethacrylate^[30] and polyvinylidene difluoride (PVDF)^[31]. Similar non-linear behaviour has also been observed in particulate composites, consisting of a (relatively) hard particle such as soda-lime glass or the explosive RDX in a rubbery binder such as HTPB^[32-34]. Bourne and Milne^[33] suggested that this deviation from a linear response was due to a transition between elastic and inelastic response in the harder phase. Bourne *et al.*^[26] suggested that similar behaviour (between the crystalline and amorphous phases) would cause the deviation from linear behaviour. For example, Brown *et al.*^[35], using in situ neutron diffraction quote elastic moduli of PTFE along the carbon backbone of *ca.* 220 GPa, whilst the corresponding property within the amorphous phase is of the order of 0.38 GPa. Clearly, the behaviour will alter as the stiffer phase changes from elastic to inelastic behaviour. It would therefore seem likely that the non-linear behaviour observed in the composite materials is also responsible for high zero particle velocity intercept of the U_S - u_p curve. However, due to the differences in length scale between on one hand rigid particles in an elastomeric binder in the case of composites, and crystallites in an amorphous matrix in the case of semi-crystalline polymers likely result in this shift from linear behaviour in

polymers occurring at such low particle velocities that it is possible that the non-linear region is missed (with one or two possible exceptions such as PMMA and PVDF). An important feature in this series of experiments lies in the variation of its optical response with shock amplitude. As PCTFE has proven to be transparent to infra-red radiation, both in this work and a previous publication^[19], it was judged a worthy exercise to determine this behaviour. Plotting measured (apparent) interfacial velocities against those determined from the known impact conditions yielded a straight line (see figure 5), from which an empirical optical correction factor could be determined. A more rigorous approach using the methods of Jensen *et al.*^[24] yielded an optical correction factor, accounting for density corrections that was near identical to the empirical value. We note with interest that Dattelbaum *et al.*^[36] have performed a similar series of experiments on the co-polymer KelF-800 (a co-polymer of PCTFE and PVDF). The aim was to characterize the optical response with a view to providing an impedance matched window to a number of polymer bonded explosives. Our own results have shown that PCTFE can also be used as an optical window in future shock loading experiments, and given its close impedance match to polymer bonded explosives, PCTFE may provide a more readily available window material for such experiments.

The second series of shots was concerned with the shock induced shear strength of PCTFE. Two factors are in effect here; the variation of lateral stress, and thus shear strength behind the shock front and the variation of shear strength with impact stress. Looking at shear strength behind the shock front first, it can be seen from figure 6 that it is near constant before release waves enter the gage location. This is in contrast to many other materials, where an evolution of shear strength is observed. In metals and alloys at least, this has been equated with events occurring at a microstructural level;

dislocation motion and generation in face centred cubic metals^[37] leading to hardening or an increase in shear strength or simple dislocation motion alone acting as a stress relief mechanism in some body centred cubic metals^[38] leading to an apparent softening or decrease in shear strength behind the shock front. In polymers, similar evolutions in shear strength behind the shock front, generally hardening have been observed in a number of materials including polymethylmethacrylate (PMMA)^[39], an epoxy resin^[5], polyethylene, polypropylene and polystyrene^[40], polyether ether ketone (PEEK)^[41] and polycarbonate^[42]. In all these materials, it was suggested that this was due to chain tangling (tacticity) resulting in an increase in strength. In the case of fluorinated polymers such as PTFE^[26], Kelf-800^[43] and Viton-B^[44], the shear strength behind the shock front has been shown to be near constant. In a previous article^[26], it was suggested that the presence of large (compared to hydrogen) fluorine atoms packed around the carbon backbone, in combination with the high degree of electronegativity of fluorine would reduce the likelihood of steric interactions between adjacent polymer chains, thereby reducing or negating the increases in shear strength behind the shock front seen in other polymers. Replacing one or more fluorine atoms in the basic monomer unit can have an effect, the most striking example being that of polyvinylidene difluoride (PVDF), where two fluorines are replaced by hydrogen. In that material, a level of hardening behind the shock front was observed^[26] (most noticeable at higher pressures), and explained as a combination of greater steric interference between chains and electronic effects (due to alternating CF₂-CH₂ pairs) allowing for differences in charge density increasing the attractive forces between chains. In the case of PCTFE, the replacement of a fluorine with a chlorine appears to have little effect on strength development behind the shock front, possibly due to the similarities between fluorine and chlorine atoms. However, significant differences do

occur when we compare the variation of shear strength with impact stress, with both PCFTE and PVDF being significantly stronger. In fact, PCTFE appears to be the strongest of these materials, particularly at higher impact stresses. This may seem unexpected, since if we assume PTFE acts as the baseline material for this study, then PCTFE has undergone the least modification of the base monomer unit; one fluorine replaced by a chlorine, compared to PVDF; two fluorines replaced by hydrogens. However, flow stress data at low and intermediate strain-rates for PCTFE^[45] and both PTFE and PVDF^[46] suggests that these trends are repeated at lower strain-rates, as shown in figure 9. Although only a limited amount of data has been found, a simple relation of,

$$m = \frac{\Delta\sigma}{\Delta(\log \dot{\epsilon})}, \quad (8)$$

FIGURE 9 NEAR HERE

where m is the strain-rate sensitivity, σ the flow stress and $\dot{\epsilon}$ the strain-rate (similar to the approach taken by Walley *et al.*^[46]) shows that PCTFE also has the highest strain-rate sensitivity of *ca.* 17.4 (compared to PTFE with 2.5 and PVDF 15). The higher strength in PVDF compared to PTFE^[26] was explained in terms of a combination of increased chain tacticity (due to the alternating CH₂ CF₂ units) and local charge distributions along the polymer chain, again due to the separated CF₂ units resulting in attractive forces between chains, in addition to the existing van de Waals attractions. It would seem likely that the presence of a chlorine atom replacing a fluorine would

have a similar disruptive effect on local charge distribution, but that its effects would be less than those observed between PTFE and PVDF. However, this is clearly not the case as PCTFE has been shown to have greater strength and strain-rate sensitivity at lower strain rates^[45, 46], as well as higher shear strengths at pressure, although at present, the precise reasons are not clear.

VI CONCLUSIONS

The shock response of the semicrystalline polymer, polychlorotrifluoroethylene has been studied in terms of its equation of state, optical response and shear strength development. Hugoniot measurements have been shown to be consistent with previously published data as expected. Differences between expected velocities at the impact face and free surfaces and the measured results were explained in terms of yielding (at the free surface) and changes in refractive index in the shock loaded material (at the impact face). For this latter, an optical correction factor was calculated, both empirically (from plotting expected particle velocity against actual particle velocity) and from calculated changes in refractive index with shock induced density. Results showed that these were near identical, and overall offers the possibility that PCTFE can be used as an optical window in shock loading experiments.

Laterally mounted stress gages were used to determine the shock induced shear strength, and its variation with both time behind the shock front and longitudinal shock stress amplitude. The shear strength was observed to be effectively constant behind the shock front, in common with a number of other fluorinated polymers such as PTFE, PVDF and Viton-B, and in contrast to many other polymers such as PMMA and polycarbonate, where a hardening response has been observed. It has been

suggested that the presence of large fluorine atoms (compared to hydrogen) around the carbon-carbon backbone results in a smoother polymer chain, reducing the amount of steric interference, and allowing easier relative movement between polymer chains. However, it was also noted that PCTFE was significantly stronger than PTFE (and indeed PVDF). It is possible that the presence of a larger chlorine atom replacing a smaller fluorine would have both physical (a small degree of steric interference) and electronic effects (due to changes in local charge density) contributing to an overall strengthening. This level of strengthening has been observed to greater than that observed in PVDF, which at present is unexplained since it would be expected that PVDF, with its greater modifications of the basic PTFE monomer unit would be expected to have the greater strength. Despite this, these results are in agreement with the trends in strength variation with applied strain-rate observed at lower strain-rates.

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TABLES

Table I. Material Properties.

	PCTFE	PTFE
Density, ρ_0 (g cm ⁻³)	2.13	2.15
Longitudinal Sound Speed, c_L (mm μ s ⁻¹)	1.74	1.23
Shear Sound Speed, c_S (mm μ s ⁻¹)	0.77	0.41
Bulk Modulus, K (GPa)	4.77	2.77
Shear Modulus, μ (GPa)	1.26	0.36
Poisson's Ratio, ν	0.378	0.437

Table II. Summary of experimental data, gathered using HetV.

Impact Velocity (mm μs^{-1})	Particle Velocity (mm μs^{-1})	Measured (apparent) Particle Velocity (mm μs^{-1})	Free Surface Velocity (mm μs^{-1})	Shock Velocity (mm μs^{-1})	Pressure (GPa)	Density (g cm ⁻³)	Refractive Index
0	0	0	0	-	0	2.122	1.425
0.191	0.094 <i>0.146</i>	0.094	0.183	2.13 <i>2.27</i>	0.43 <i>0.71</i>	2.23	1.445
0.334	0.167 <i>0.252</i>	0.165	0.322	2.26 <i>2.45</i>	0.81 <i>1.31</i>	2.30	1.460
0.494	0.249 <i>0.365</i>	0.246	0.483	2.34 <i>2.49</i>	1.23 <i>2.09</i>	2.39	1.476
0.663	0.331 <i>0.478</i>	0.327	0.644	2.56 <i>3.07</i>	1.80 <i>2.92</i>	2.45	1.490
0.803	0.400	0.395	0.775	2.61	2.23	2.52	1.504

Values in italics are from the second shock.

Table III. Summary of experimental data gathered using stress gages. Gage separation is nominally 2 mm.

Impactor (mm)	Impact Velocity (mm μs^{-1})	Particle Velocity (mm μs^{-1})	Shock Velocity (mm μs^{-1})	Longitudinal Stress (GPa)	Lateral Stress (GPa)	2 Tau (GPa)
Al, 10	0.368	0.279	2.50	1.42	0.99	0.43
Cu, 10	0.470	0.406	2.89	2.32	1.60	0.72
Cu, 10	0.529	0.460	2.94	2.67	1.90	0.77
Cu, 10	0.687	0.585	2.41*	3.9	2.63	1.27
Cu, 10	0.812	0.679	2.94*	5.16	3.06	2.1

*These shock velocities are erroneous most likely due to movement of the lateral stress gages from their nominal position during assembly.

FIGURE CAPTIONS

Figure 1. Schematic diagram of equation of state experiments of PCTFE.

a. Half section

b. Rear view

Figure 2. PCTFE longitudinal and lateral stress gage target assemblies.

a. Schematic target assembly.

b. Target assembly in-situ.

Figure 3. HetV results from PCTFE impacted at 190.3 m s^{-1} .

a. Spectrogram

b. Extracted data

Figure 4. Schematic $X-t$ diagram of equation of state experiment.

Figure 5. Optical changes in PCTFE as a function of shock loading.

a. Apparent versus true particle velocity b. Refractive index versus shocked density.

Figure 6. Longitudinal and lateral stress gage traces from PCTFE, using a 10 mm dural flyer at 368 m s^{-1} .

Figure 7. Shock Hugoniot data for polychlorotrifluoroethylene.

a. Shock velocity – particle velocity

b. Stress and pressure – particle velocity.

Figure 8. Shear strength of PCTFE as a function of shock stress. Data from PTFE^[26] and PVDF^[31] are included for comparison.

Figure 9. Flow stress versus strain-rate for PCTFE^[45] and PTFE and PVDF^[46] at low and intermediate strain-rates. Straight lines have been fitted to indicate trends.

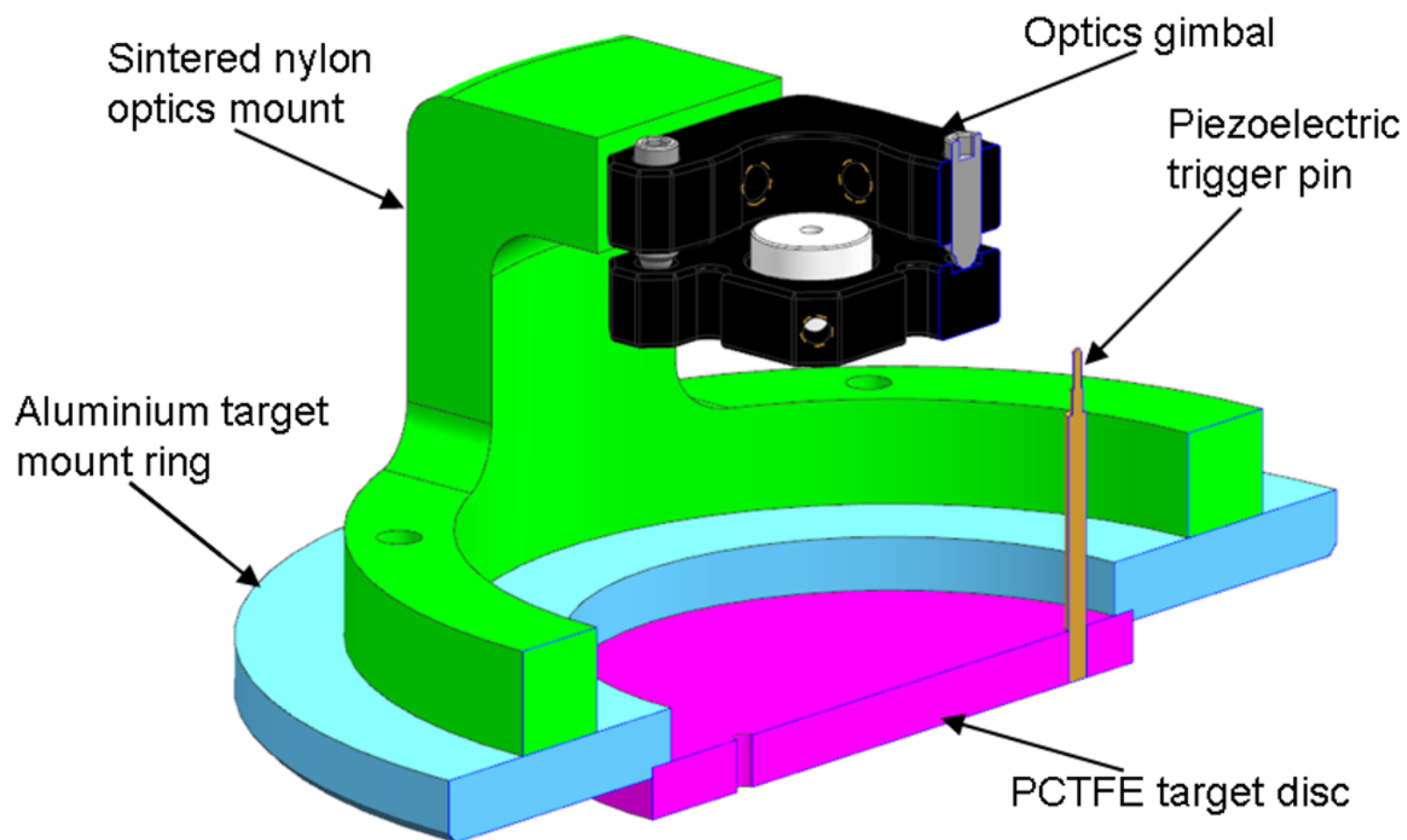


Figure 1. Schematic diagram of equation of state experiments of PCTFE.
a. Half section□

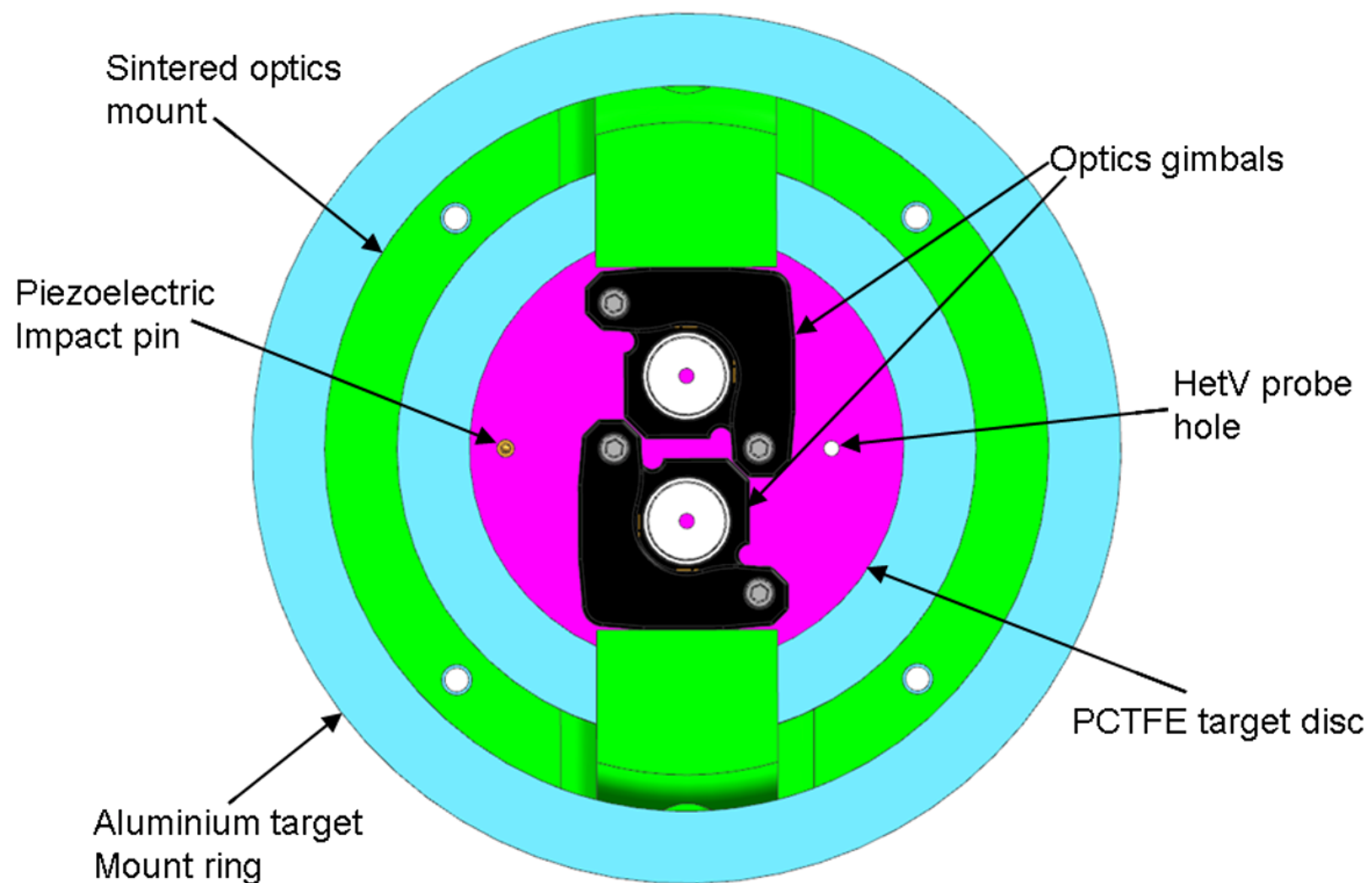


Figure 1. Schematic diagram of equation of state experiments of PCTFE. b. Rear view

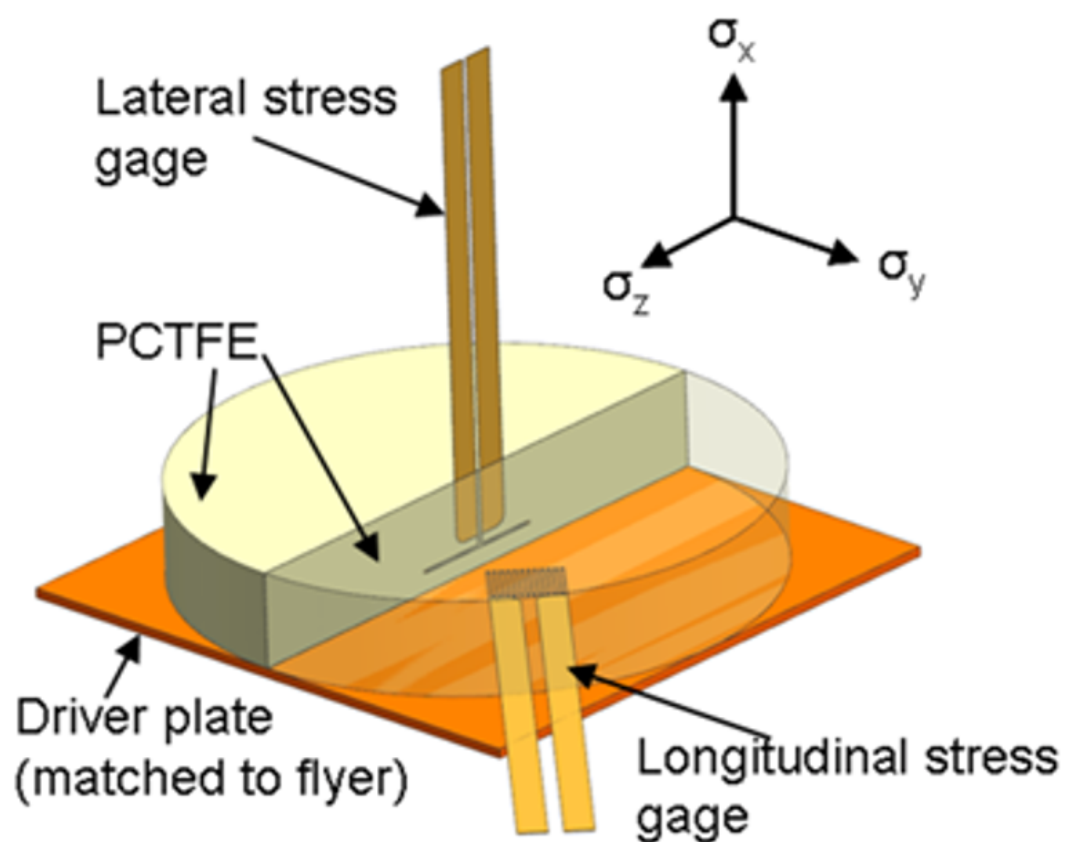


Figure 2. PCTFE longitudinal and lateral stress gage target assemblies.

a. Schematic target assembly.

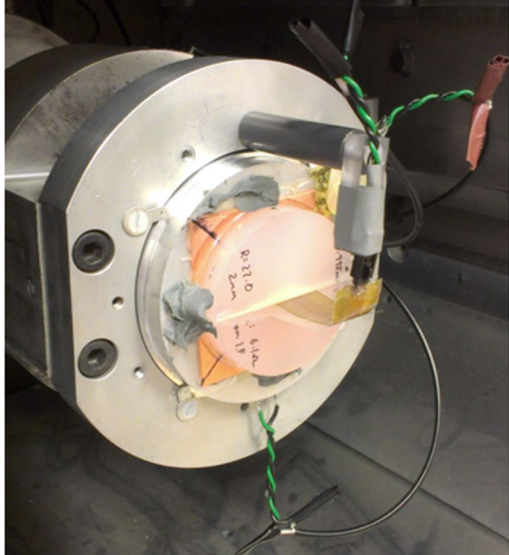


Figure 2. PCTFE longitudinal and lateral stress gage target assemblies.

b. Target assembly in-situ.

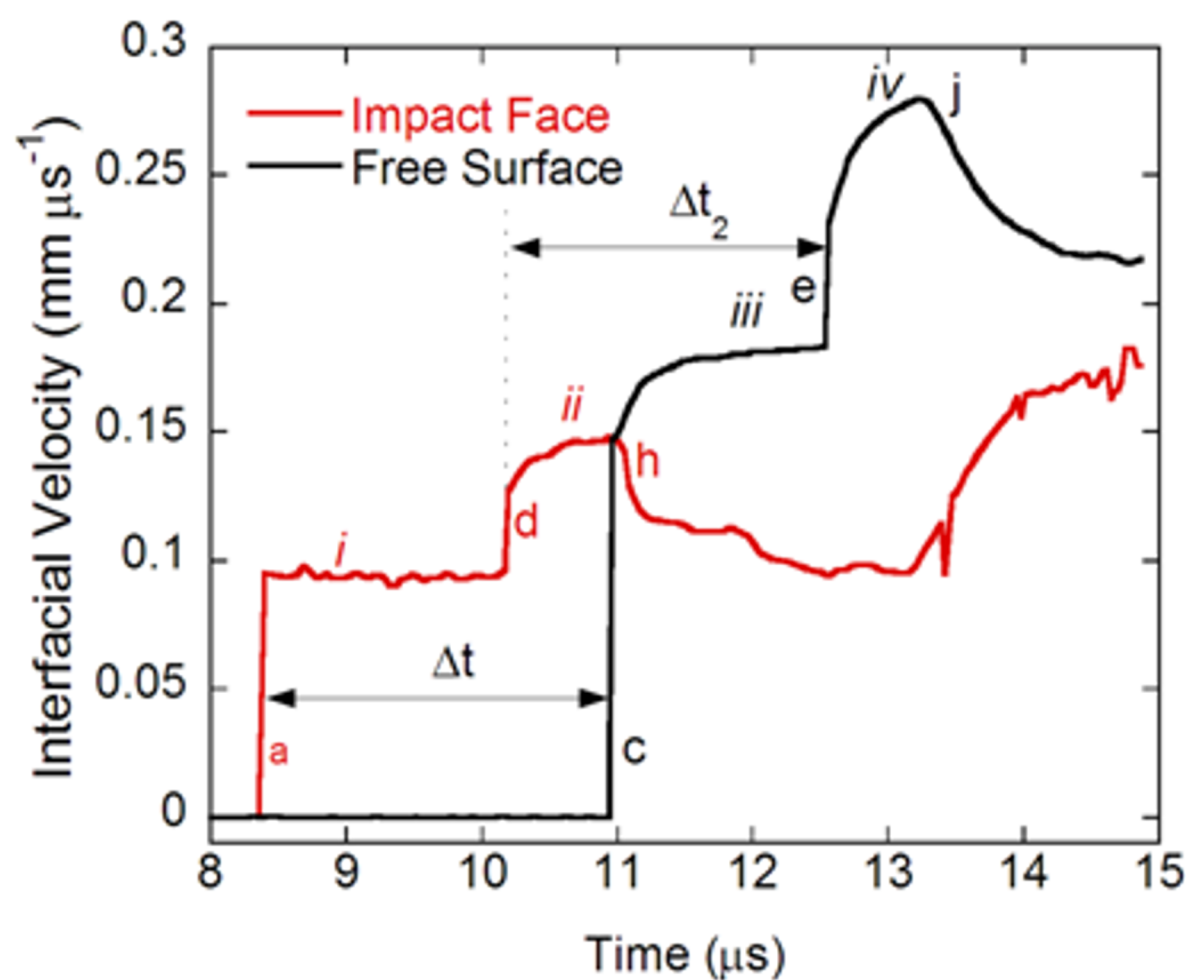


Figure 3. HetV results from PCTFE impacted at 190.3 m s^{-1}

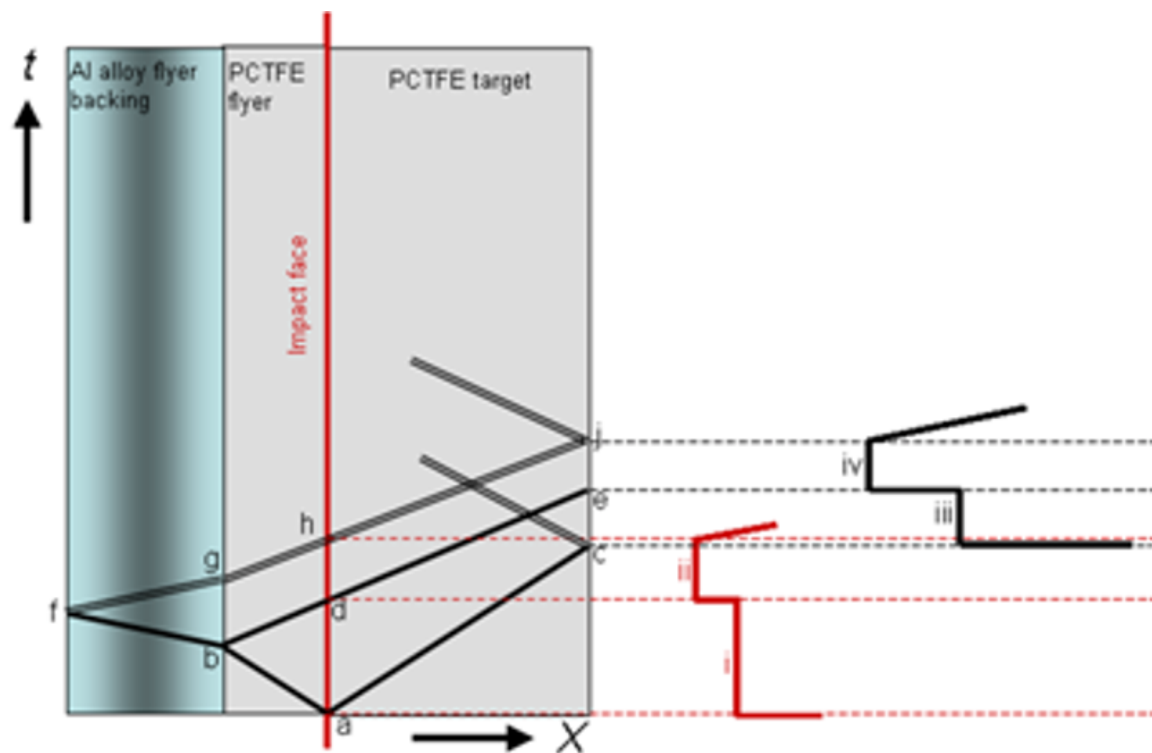
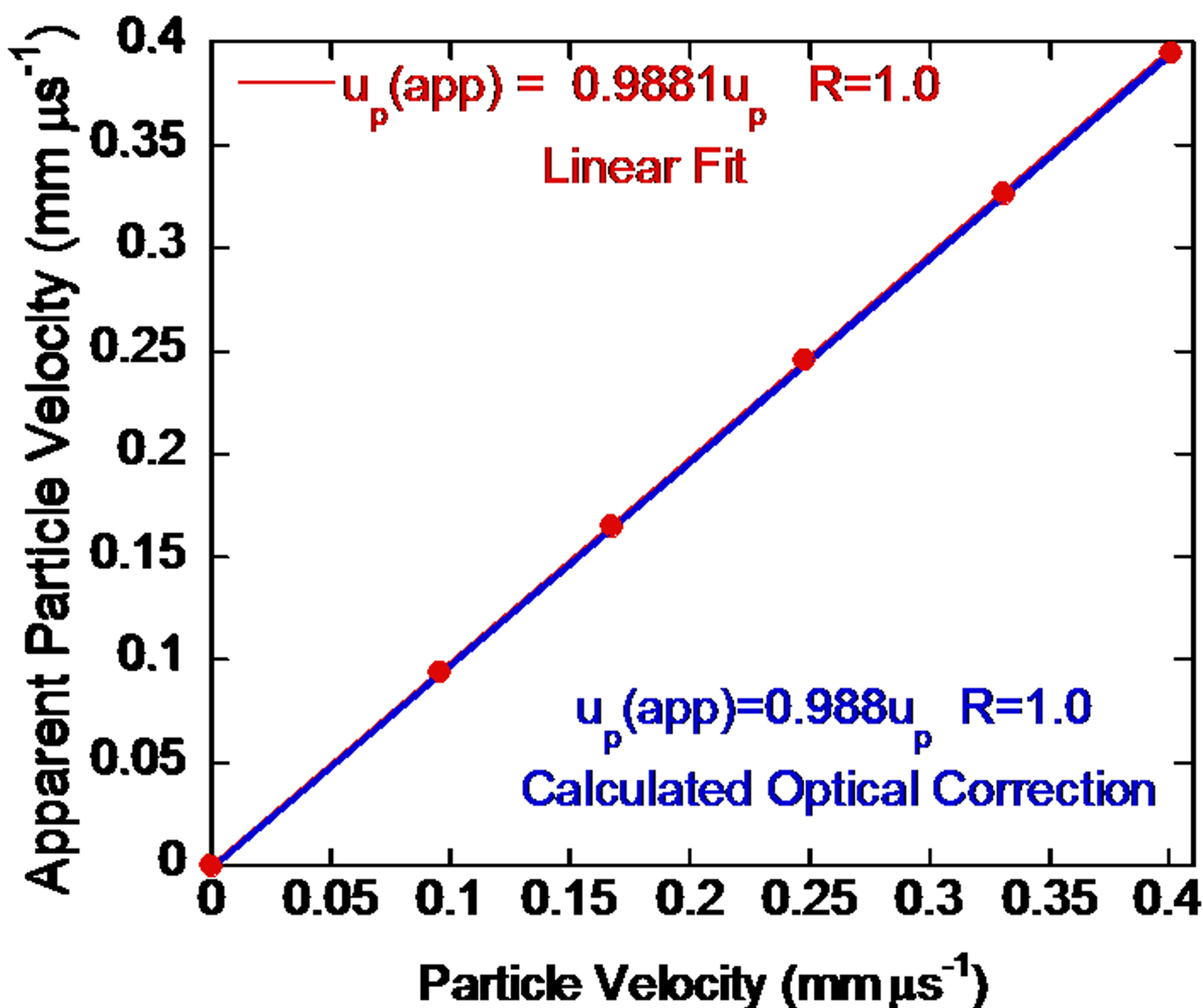


Figure 4. Schematic X - t diagram of equation of state experiment.



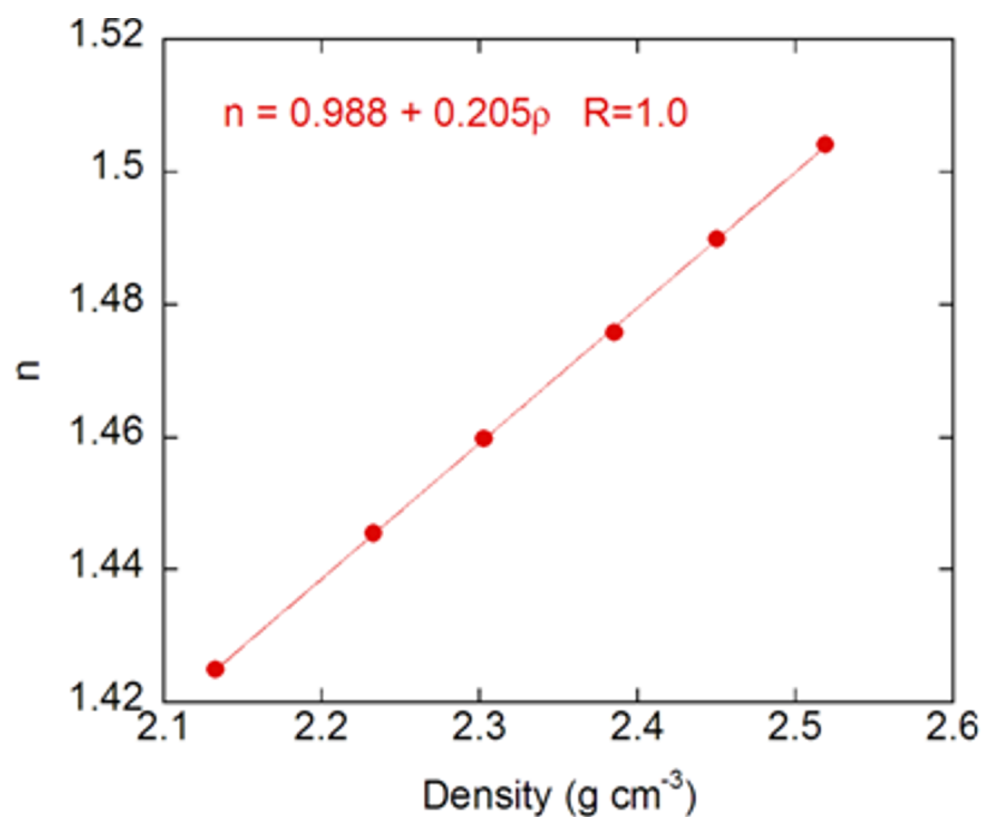


Figure 5. Optical changes in PCTFE as a function of shock loading.
b. Refractive index versus shocked density.

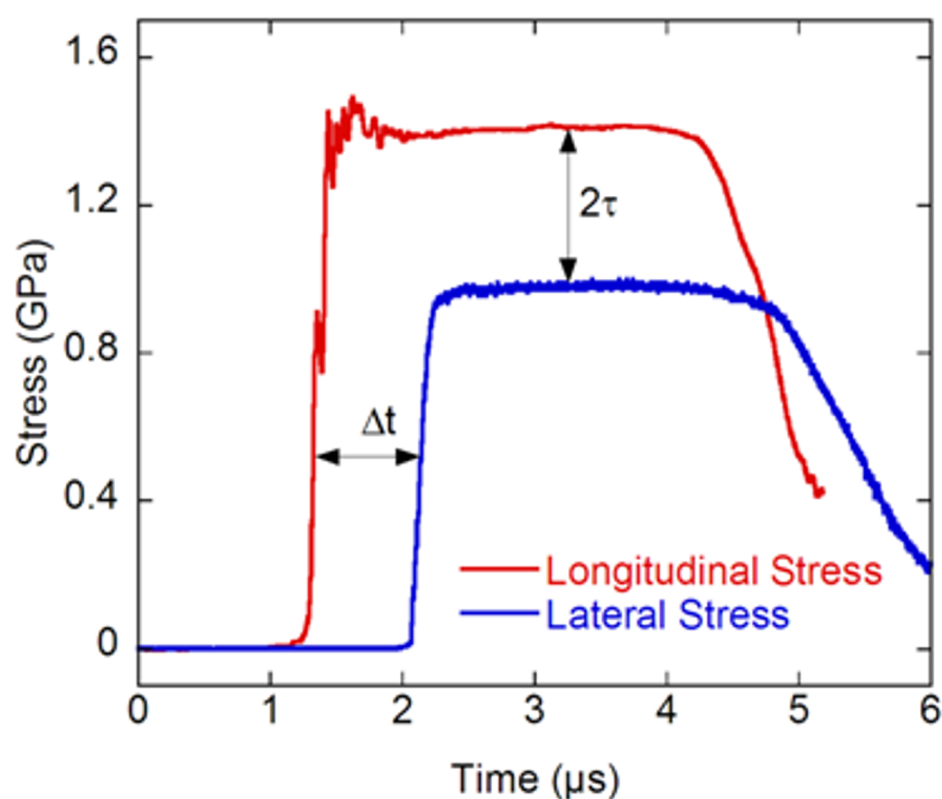


Figure 6. Longitudinal and lateral stress gage traces from PCTFE, using a 10 mm dural flyer at 368 m s^{-1} .

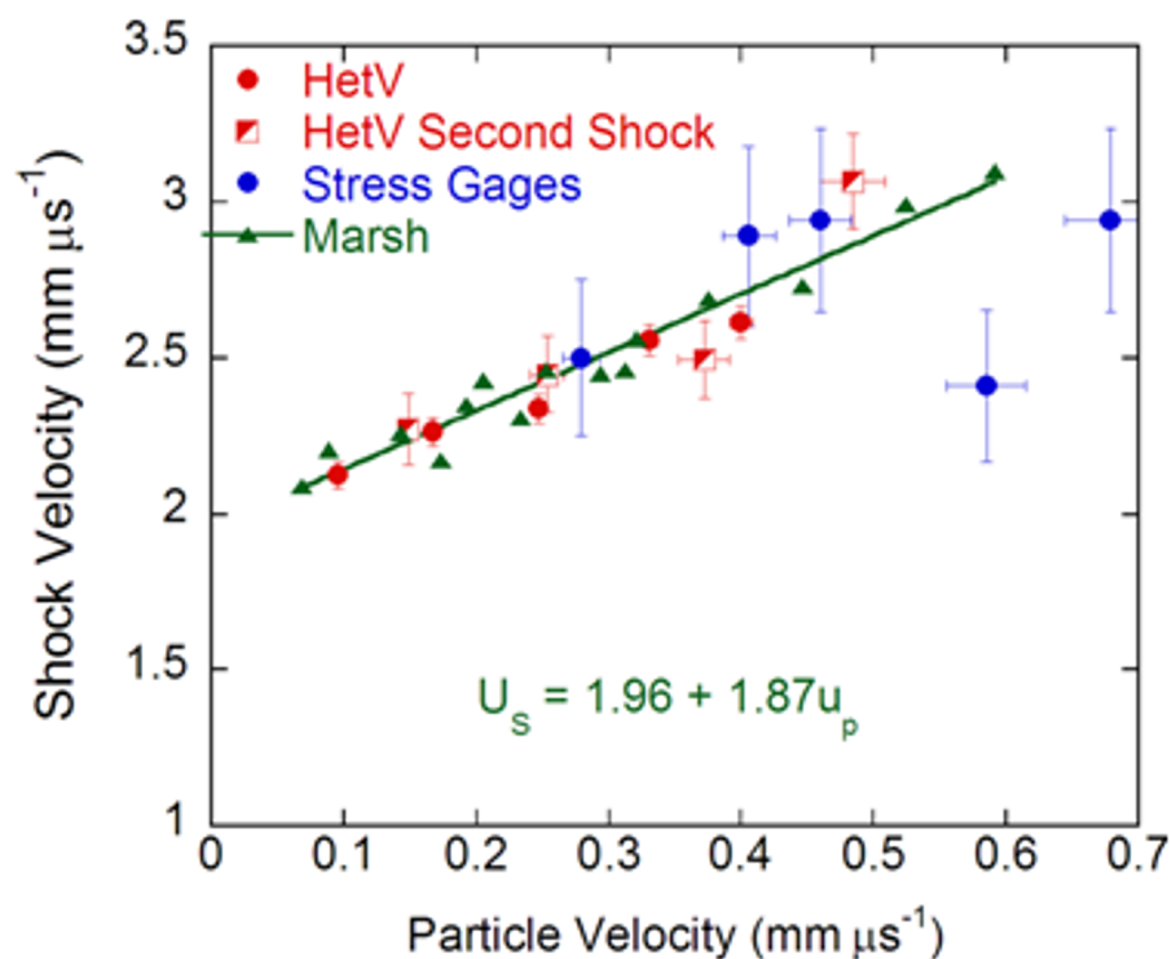


Figure 7. Shock Hugoniot data for polychlorotrifluoroethylene.
a. Shock velocity – particle velocity

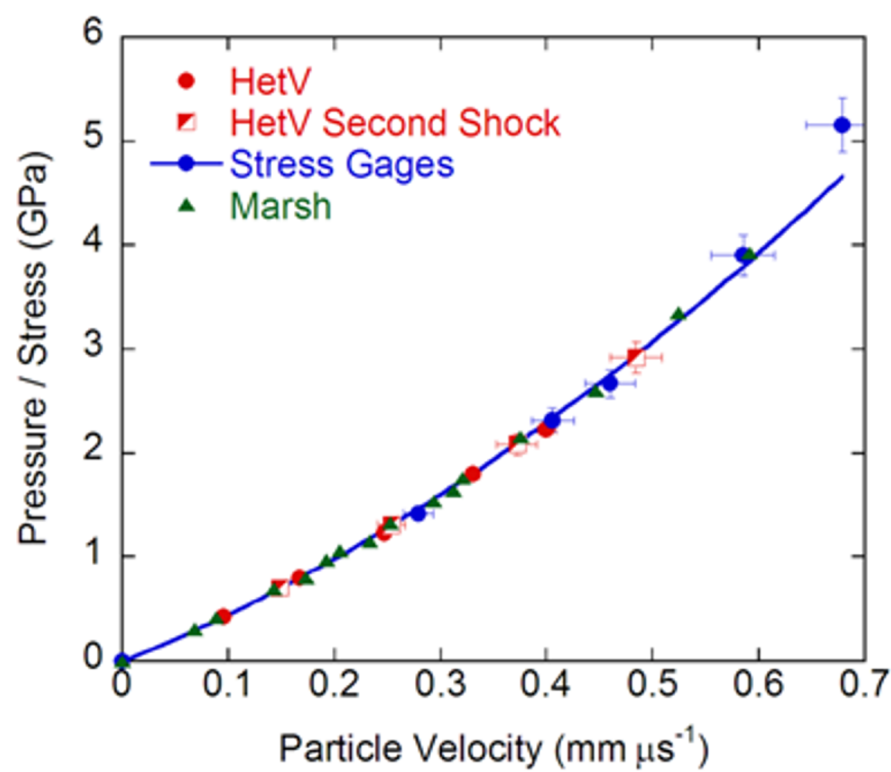


Figure 7. Shock Hugoniot data for polychlorotrifluoroethylene.
b. Stress and pressure – particle velocity.

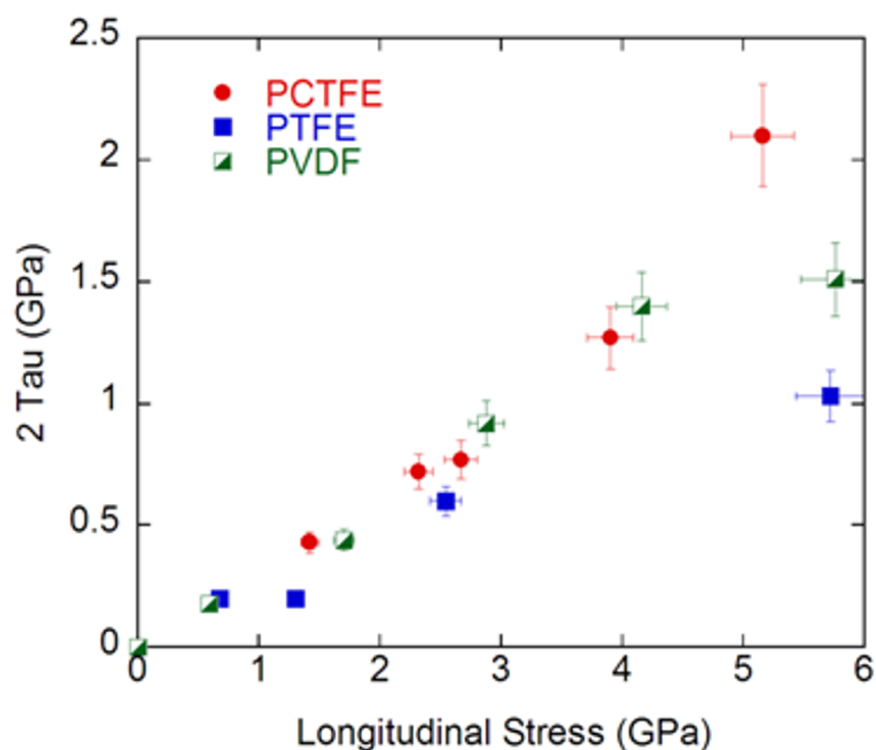


Figure 8. Shear strength of PCTFE as a function of shock stress. Data from PTFE^[26] and PVDF^[27] are included for comparison.

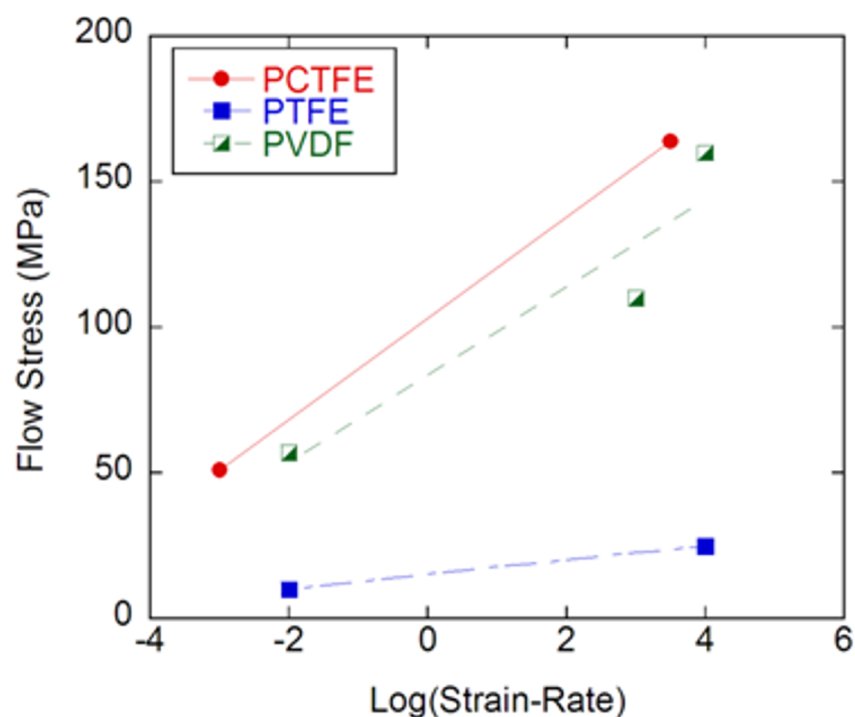


Figure 9. Flow stress versus strain-rate for PCTFE^[44] and PTFE and PVDF^[45] at low and intermediate strain-rates. Straight lines have been fitted to indicate trends.



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