Investigation on the Strain Rate Sensitivity of Polytetrafluoroethylene

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Keywords: Polytetrafluoroethylene, Strain rate sensitivity, Experiment.

Abstract. Strain rate sensitivity of polytetrafluoroethylene (PTFE) across strain rate range from 10^{-3} to 10^{6} s^{-1} was investigated. For quasi-static state of strain rates from 10^{-3} to 10^{-1} s^{-1}, the samples were tested using universal material testing machine. The values of compression strength and Young’s Modulus were calculated from the experimental results. And exponential fitting and linear fitting were done to the experimental data of compression strength and Young’s Modulus, respectively. The quasi-static experimental results are compared with Zerilli-Armstrong model for polymers, which shows better agreement at large strains. For 10^{2}~10^{3} s^{-1}, the samples were tested using traditional split Hopkinson pressure bars (SHPBs). The experimental result was compared with other test of as-received sample. For 10^{5}~10^{6} s^{-1}, the PTFE dynamic pressure experiment was conducted using pressure-shear-plate-impact (PSPI) facility. The polymer-specific Lennard-Jones model was used to analyze the results of ultra-high strain rate.

Introduction

Polytetrafluoroethylene (PTFE), or Teflon has many advantages. It has been used in many fields, usually as manufacture and engineering parts because of its insolubility in all common solvents, resistance to almost all acidic and caustic materials, a very high dielectric strength, low dielectric loss, low coefficient of sliding friction and so on. And over the past decade, it has been used in military as a component of reactive material because the materialist intended to be inert under quasi-static or static loads, and the mechanical work of a high-strain-rate plastic deformation process will provide the energy required to drive the reaction. In many studies, energy release characteristics of this type of impact-initiated reactive material is important. Some research results have been published. In addition, PTFE suffers complex dynamic loads across large strain rate range in all cases. So many investigations have been carried out on the strain rate sensitivity of PTFE.

Akhtar Khan and Haoyue Zhang tested and modeled the response of the strain rate hardening, creep, and relaxation behaviors of PTFE. Jennifer L. Jordan, et al., gave an investigation of the properties of PTFE across strain rates from 10^{-3} to 10^{5} s^{-1}. A miniaturized SHPB was employed for ultra-high strain rates. P.J. Rae and D.M. Dattelbaum, using a Split-Hopkinson pressure bar, studied the compression properties of PTFE at strain-rates between 10^{-4} and 1 s^{-1}. They found that the mechanical properties of PTFE were strongly affected by strain-rate. A miniaturized SHPB was employed for ultra-high strain rates 10^{4}~10^{5} s^{-1}. The Zerilli-Armstrong model was used to analyze the results of the experiments, which shows good agreement with other PTFE test studies. This model was also chosen for comparing with test data of strain rates from 10^{-3} to 10^{3} s^{-1} this study. When it refers to uniaxial stress case, the visco-elastic part of Zerilli-Armstrong constitutive model can be reduced as,

\[
\sigma_{11}^{(k)} + \sigma_{11}^{(k)} = \frac{3G_{1}K}{\tau_{k}}\left(\dot{e}_{11} - \dot{e}_{11}^{(p)}\right) + \frac{G_{k}}{3(K + \frac{1}{3}G_{0})} \sum_{k=1}^{n} \sigma_{11}^{(k)} \tau_{k}^{*}, k = 1, ..., n
\] (1)

And
\[ \sigma_{11} = \sigma_p \left( \varepsilon^{(p)}, \dot{\varepsilon}^{(p)} \right) \]  

(2)

Where \( \varepsilon \) and \( \dot{\varepsilon} \) are the strain and strain rate, \( K \) is the volume and temperature dependent bulk modulus, the sub/superscript \( p \) indicates the plastic component of the stress and strain, the sub/superscript \( k \) represents the Maxwell-Weichert elements, respectively, and \( \tau_k \) is the relaxation times of the Maxwell-Weichert elements, \( G_k \) and \( G_0 \) are the modulus of the Maxwell-Weichert elements, and \( G_0 = \sum_{k=1}^{n} G_k \).

The visco-plastic part of Zerillie-Armstrong constitutive model can be expressed as [9],

\[ \sigma = B e^{-\beta T} + B_0 \sqrt{1 - e^{-\omega \varepsilon}} / \omega e^{-\alpha T} \]  

(3)

Where \( \omega \) is the rate for mobilization of flowunits, \( B, B_0, \alpha, \) and \( \beta \) are material constants.

Many useful conclusions have been received across strain rate range from \( 10^{-4} \) to \( 10^5 \) s\(^{-1}\). However, until recently, there is little information available in literature about higher strain rate range of \( 10^5 \) to \( 10^6 \) s\(^{-1}\). To study the deformation properties of PTFE at ultra-high strain rate up to \( 10^6 \) s\(^{-1}\) becomes very important when suffered local large deformation of usual loads or explosive loads. A polymer-specific Lennard-Jones model [10] for the pressure-volume response can be employed to identify the experimental result at ultra-high strain rate \( 10^5 \) to \( 10^6 \) s\(^{-1}\) [11], which can be represented as

\[ p = A \left( J^{-N-1} - J^{-M-1} \right) \]  

(4)

Where \( A, M, \) and \( N \) are material constants.

In this paper, the strain rate sensitivity of PTFE across strain rates from \( 10^{-3} \) to \( 10^6 \) s\(^{-1}\) was studied. For quasi-static state of strain rates from \( 10^{-3} \) to \( 10^{-1} \) s\(^{-1}\), the samples were tested using universal material testing machine. For \( 10^2 \) to \( 10^3 \) s\(^{-1}\), the samples were tested using traditional split Hopkinson pressure bars (SHPBs). For \( 10^5 \) to \( 10^6 \) s\(^{-1}\), the PTFE dynamic pressure experiment was conducted by employing pressure shear plate impact (PSPI) facility. And the Zerillie-Armstrong model for polymers was chosen to compare with quasi-static experimental results. The polymer-specific Lennard-Jones model was used to analyze the results of ultra-high strain rate.

**Experiment Techniques**

**Test Materials**

The industrially produced 0.75" diameter PTFE rod [12] of McMaster-Carr was machined into cylinder samples. For universal material testing machine tests, the samples has a diameter of 10mm and a length of 10mm according to GB/T1039-1992. The ratio of diameter over length is 1:1. For SHPBs tests, the diameter is 20mm and the lengths are 10mm and 5mm, respectively. The ratio of diameter over length are 1:0.25 and 1:0.5, respectively, which are bigger than the aspect ratio of 1:1 used in literature[8], according to which the ratio cannot be smaller than 1:1.5, or the sample will tend to deform by a term of mixture of shearing and compression rather than by the expected uniaxial compression. Depending on strain rate, the samples with different lengths were positioned between the incident and transmitted bars. For the ultra-high strain rate of \( 10^5 \) to \( 10^6 \) s\(^{-1}\), 0.4 mm thick PTFE film [10] of McMaster-Carr was used, which was made into plates with the diameter size of \( \Phi 50 \) mm. All the samples were tested at as-received state, at room temperature.

**Test Facilities**

For quasi-static state of strain rates from \( 10^{-3} \) to \( 10^{-1} \) s\(^{-1}\), the samples were tested using universal material testing machine facility, which can be seen in Fig 1. The samples were quasi-static loaded. The compression ratio is 0.6, 6, and 60 mm/min, respectively. According to Equation (4), The correspond strain rate is 0.001 s\(^{-1}\), 0.01 s\(^{-1}\), and 0.1 s\(^{-1}\), respectively. The strain in the sample was determined from the crosshead displacement, and the stress was determined from the load cell output.
\[ \dot{\varepsilon} = \frac{v_l}{L_s} \]  

Where \( \dot{\varepsilon} \) is loaded strain rate, \( v_l \) is load velocity of the crosshead, and \( L_s \) is the length of the sample.

For strain rates from \( 10^{-3} \) to \( 10^4 \text{s}^{-1} \), the samples were tested using traditional split Hopkinson pressure bars (SHPBs) facility, a schematic diagram of which is shown in Fig.2. The setup consists of incident and transmitted bars of with the same diameter of 36mm, the same length of 2,000 mm, and the same material of 6061-T6 aluminum. The impact bar is 800 mm long and made of the same material as the other bars. The incident, reflected, and transmitted signals are recorded by strain gages, which determine the sample properties. These signals are recorded by the Data System, like Fig.3 shows. The incident and reflected signals are recorded by CH1 channel and the transmitted signal is recorded by CH2 channel. The test data is analyzed by a software named BIT.D-Wave.

For higher strain rates \( 10^5 \text{~} \text{to} \text{~} 10^6 \text{s}^{-1} \), the sample experiment was conducted using pressure shear plate impact (PSPI) facility. The setup is shown in Fig.4. A very thin sample of PTFE film is
sandwiched between the front plate and the rear plate. The material of the flyer, front plate and rear plate is tungsten carbide #504, with density of 15.4g/cm³ and longitudinal wave speed of 6.69mm/µs. The rear surface is mirror polished. The normal velocity at the back surface is recorded by interferometer, called NDI [14]. The experiment conditions for the shot is listed in Table.

![Figure 4. Schematic diagram of PSPI facility setup](image)

Table 1. Experiment conditions for PSPI test

<table>
<thead>
<tr>
<th>Shot number</th>
<th>h (mm)</th>
<th>hfront (mm)</th>
<th>hrear (mm)</th>
<th>hflyer (mm)</th>
<th>ϕ (mm)</th>
<th>Plates material</th>
<th>v₀ (m/s)</th>
<th>Tilt (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1301</td>
<td>0.4</td>
<td>4.016</td>
<td>4.026</td>
<td>4.021</td>
<td>50</td>
<td>WC#504</td>
<td>186.7</td>
<td>&lt;0.7</td>
</tr>
</tbody>
</table>

Experimental results and analysis

**Experimental results**

The as-received PTFE samples were tested on SHPBs facility at room temperature across strain rates from 10⁻³ to 10⁶s⁻¹. The results of strain rates from 10⁻³ to 10³s⁻¹ are shown in Fig.5. At each strain rate, at least three samples were tested until there were three curves in good uniformity. The curves in the figure represent averages of three experiments. With the increase of strain rate, the PTFE material showed obvious strengthening behavior.

![Figure 5. Stress verses strain of McMaster-Carr PTFE across strain rates 10⁻³~10³s⁻¹ at room temperature](image)

The results of experimental and Lennard-Jones model of strain rates from 10⁻⁵ to 10⁶s⁻¹ are displayed in Fig.6. The parameter values of A, M, and N for the Lennard-Jones model are: A=2.5GPa, M=3, and N=5. The isentrope has a kink in it at a strain of approximately 0.12. This is
because once the shot begun, the status of the stress and strain became from the initial status of zero to the kink. There were no more data between zero and the kink, which can be smoothed by difference calculation.

The rapid deformation and increasing pressure during the test will cause the temperature of the sample up. PTFE will experience phases change with increasing temperature. According to the thesis of Stephen E. Grunschel [15], the temperature change $dT$, in term of plastic work and pressure change, is obtained from

$$dT = \frac{\tau d\bar{\gamma}_p + T dP}{\rho_0 c_p}$$

(5)

Where $\tau$ and $\bar{\gamma}_p$ is the effective stress and effective strain, respectively, and this part was zero for this test; $\alpha$ is the coefficient of the thermal expansion and $c_p$ is the heat capacity at constant pressure. Based on the experimental data, the result is shown in Fig.7.

PTFE is a complicated semi-crystalline polymer. A phase diagram which consists of four solid phases and one liquid phase has been established through previous volume measurements over a wide range of temperature and pressure [16-17]. H. D. FLACK [18] described a phase of high-pressure up to 25 kbar of PTFE. According to McCrum [19], whose paper presented a research of internal friction in polytetrafluoroethylene from 4.2K to the crystalline melting point at 600K, there was a transition at 400k during the experimental process. The temperature of the sample rose by 200K during the process of the experiment (Fig.7). The maximum temperature value was under the crystalline melting point.

The values of compression strength and Young’s Modulus at quasi-static state were calculated
from the experimental state, which are listed in Table 2. The values in the figure represent averages of three experiments. Exponential fitting was made to the experimental data of compression strength. Young’s Modulus increases almost linearly with the strain rate. The results are shown in Fig.8.

<table>
<thead>
<tr>
<th>Strain rate(s⁻¹)</th>
<th>Compression strength (MPa)</th>
<th>Young’s Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>85.2</td>
<td>233.6</td>
</tr>
<tr>
<td>0.01</td>
<td>116.9</td>
<td>250.9</td>
</tr>
<tr>
<td>0.1</td>
<td>178.2</td>
<td>346.3</td>
</tr>
</tbody>
</table>

Figure 8. Mechanics performance parameters of PTFE versus strain rate at quasi-static state

Comparison with Other Experimental Results

The experimental results was compared with the test of as-received sample in Reference [7], which is shown in Fig.9. It can be seen that the material of McMaster-Carr PTFE has consistently higher strength than the as-received PTFE material. Generally, it is thought that the strength of PTFE is proportional to the crystallinity percentage [8]. However, the opposite was published [11], which studied the properties of other semi-crystalline. In addition, the processing route used to prepare the PTFE can greatly affect the crystallinity percentage of the material. All these factor should be considered when carrying out further research.

Figure 9. Comparison experimental results between the current test and the test in Literature 3
Application of Zerilli-Armstrong model

The Zerilli-Armstrong model describes the stress-strain behavior of polymers as a function of temperature, strain-rate, and superposed hydrostatic pressure under condition of ignoring creep and long-term relaxation effects. The model was implemented by Matlab programming. The Matlab-based code solves Equation (1)-(3), using a built-in explicit fourth order Runge-Kutta solver. The total strain rate is assumed to be constant. The constants in Equation (1)-(3) are the same as that published in Reference[9] except $B_{pa}$, $B_{0pa}$, $B_{pn}$, and $B_{0pn}$, the values are 4 Mpa,7,0.5 Mpa and 0.47.Comparison was only made with quasi-static experimental data, which can be seen in Fig.10. The curves shows better agreement at large strains.

![Figure 10. Comparison of Zerilli-Armstrong model with quasi-static experimental data](image)

Conclusion

Strain rate sensitivity and the critical state of shape failure of McMaster-CARRPTFE across strain rate range from $10^{-3}$ to $10^{6}$ s$^{-1}$ was investigated. The compression strength changes exponentially with the strain rate and Young’s Modulus changes linearly with the strain rate for quasi-static state of strain rates from$10^{-3}$ to $10^{-1}$ s$^{-1}$. Compared with Zerilli-Armstrong model for polymers, the quasi-static experimental results show better agreement at large strains. For $10^{2} \sim 10^{3}$ s$^{-1}$, the samples were tested using traditional split Hopkinson pressure bars (SHPBs). For $10^{5} \sim 10^{6}$ s-1, the PTFE dynamic pressure experiment was conducted using pressure-shear-plate-impact (PSPI) facility. We recognize that a single PSPI test may not be enough to get the isentrope for PTFE. We suggest that experiments be repeated using a wider range of initial conditions. And it would be interesting to perform research on the validation of the model used in the case of pressure-shear condition.

Acknowledgements

This work is financially supported by the national project of natural science (11172071). I am grateful to Professor Rodney Clifton, Professor Jiao tong, Dr. Liu Chunmei and Dr. Ren Yu for their support of the test facility, and Dr. Baiyang, Dr. Song qing, and Dr. Ge chao for their test assistance.

References


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[12] More about plastic. Copyright © 2012 McMaster-Carr Supply Company. All rights reserved.


