Effects of Strain Rate on the Compressive Stress-Strain Loops of Several Engineering Plastics

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Abstract
Compressive stress-strain loops of several commercial engineering plastics at strain rates of up to 600/s are determined using the standard split Hopkinson pressure bar. Four different engineering plastics or typical thermoplastics: PA-6, PA-66, PC and POM are tested at room temperature. Cylindrical specimens with a slenderness ratio (= length /diameter) d of 0.5 are used in the Hopkinson bar tests, and those with l/d = 1.5 as specified in the ASTM Designation E9-89a are used in the static tests. The stress-strain loops in compression at low and intermediate strain rates are measured on an Instron testing machine. The effects of strain rate on the Young’s modulus, flow stress at 2.5% strain and dissipation energy are investigated. It is demonstrated that the area included within the stress-strain loop (or dissipation energy) increases with increasing strain rate as well as given strain, that is, all plastics tested exhibit intrinsic strain-rate dependent viscoelastic behavior and a high elastic aftereffect following complete unloading.

Key words
Compressive Properties, Engineering Plastics, Hopkinson Bar, Strain Rate, Stress-Strain Loops, Viscoelasticity

1. Introduction
Polymeric materials with low mechanical impedance have been widely used in automotive, aerospace and portable electronics applications for shock and vibration absorption. In order to ensure the structural integrity of these applications from the product design stage, it is needed to have precise knowledge of the stress-strain and energy dissipation behavior of these materials under impact loading. The dynamic compressive [1-7, 9-13], tensile [12] and torsional [8] stress-strain responses of various polymers have often been determined with the conventional or modified split Hopkinson pressure bar (SHPB). The strain rate and temperature dependence of the compressive properties of PE, PEEK and PEEK were examined using a drop-weight apparatus [14, 15]. However, most of the previous studies focused only on the dynamic stress-strain behavior during loading, and did not consider that during dynamic unloading. As a consequence, the dynamic energy absorption characteristics of polymeric materials have not been well understood as yet.

The purpose of the present paper is to determine the complete stress-strain loops in compression of several engineering plastics at strain rates of up to 600/s using the conventional SHPB. Four different plastics or PA-6 (Polyamide-6), PA-66, PC (Polycarbonate) and POM (Polyoxymethylene) were tested at room temperature. Cylindrical specimens with a slenderness ratio l/d (length/diameter) of 0.5 were used in the SHPB tests, and those with l/d = 1.5 as specified in the ASTM Designation were used in the static tests. The compressive stress-strain loops at low and intermediate strain rates were measured on an Instron 5500 R testing machine. The influences of strain rate on the Young’s modulus, flow stress at 2.5% strain and dissipation energy were studied. It is shown that the area enclosed by the stress-strain loop increases with increasing strain rate as well as given strain, that is, all plastics tested display intrinsic strain-rate dependent viscoelastic behavior and delayed reversible deformation following complete unloading.

2. Experimental Procedures
2.1 Test polymers and specimen preparation
Four different commonly used plastics, i.e., PA-6, PA-66, PC and POM were chosen for compression testing at room temperature. Cylindrical specimens were machined out of commercial extruded bars with a diameter of nearly 10 mm into short cylinders with a diameter of 9 mm. The impact specimen’s length was determined so that the slenderness ratio of l/d (d = 9 mm) value is equal to 0.5, which corresponds to the optimum specimen geometry for metallic materials suggested by Davies and Hunter [1]. The static specimen’s length was determined to be l/d = 1.5 in accordance with the ASTM Designation E9-89a [16]. The specimen end surfaces were polished with #1500 emery paper and then buffed on a buffing wheel.

2.2 Low strain-rate compression testing
In order to examine the effect of specimen’s slenderness ratio l/d on the static stress-strain hysteretic behavior, preliminary compression tests were first carried out on PC specimens with two different slenderness ratios on the Instron 5500 R testing machine. A thin layer of lubricant

![Fig. 1 Effect of specimen geometry on static compressive stress-strain loops for PC](image-url)
Table 1 Static compressive and physical properties of four different plastics tested

<table>
<thead>
<tr>
<th>Engineering plastic</th>
<th>Young’s modulus $E$ (GPa)</th>
<th>Proof strength $\sigma_{0.2}$ (MPa)</th>
<th>Compressive strength $\sigma_c$ (MPa)</th>
<th>Dissipation energy $U_d$ (MJ/m$^2$) ($\xi = 0.10$)</th>
<th>Glass transition temperature $T_g$ ($^\circ$C)</th>
<th>Mass density $\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA-6</td>
<td>1.7</td>
<td>29.6</td>
<td>N/A (78)*</td>
<td>2.88</td>
<td>50</td>
<td>1130</td>
</tr>
<tr>
<td>PA-86</td>
<td>1.6</td>
<td>28.2</td>
<td>N/A (89)</td>
<td>2.69</td>
<td>50</td>
<td>1140</td>
</tr>
<tr>
<td>PC**</td>
<td>1.8</td>
<td>52.2</td>
<td>73.3 (76-86)</td>
<td>4.37</td>
<td>150</td>
<td>1200</td>
</tr>
<tr>
<td>POM</td>
<td>2.3</td>
<td>43.4</td>
<td>N/A (107)</td>
<td>4.51</td>
<td>-56</td>
<td>1420</td>
</tr>
</tbody>
</table>

* Note: values in parentheses are provided by manufacturers; ** non-crystalline polymer

(MoS$_2$) was applied to the anvil/specimen interfaces to minimize frictional constraints. Typical two static compressive stress-strain loops of PC are given in Fig. 1. An initial ascending and a final descending portion of the stress-strain curve from the PC specimen with $l/d = 0.5$ are slightly underestimated and overestimated compared with those with $l/d = 1.5$. This is because the frictional effects between the specimen’s ends and the anvils of the machine become less negligible as the $l/d$ value gets lower even if lubricant is used. This suggests that the ASTM E9-89a recommendations for the slenderness ratio of cylindrical specimens are quite appropriate for polymeric materials as well as metallic materials. Accordingly, all the low strain-rate compression tests were performed on the specimens with $l/d = 1.5$ using the Instron 5500R testing machine at a constant crosshead speed of 1mm/min. The specimens were loaded up to a strain of nearly 10% and unloaded at the same crosshead speed. The full compressive stress-strain loops of the four different plastics are shown in Fig. 2. All the stress-strain loops are not closed, that is, elastic reversible strains remain in the specimens just after unloading, but these strains are soon recovered to zero. This behavior is known as an elastic aftereffect [17]. The static compressive and physical properties are listed in Table 1. Note that POM has the highest Young’s modulus and the largest dissipation energy at a given strain of around 10% among the four plastics tested.

2.3 High strain-rate compression testing

In the present SHPB testing, a 2024-T4 Al alloy Hopkinson pressure bar with low mechanical impedance is used to reduce the drastic impedance mismatch between the specimen and the metallic bars, which results in a transmitted strain signal with a very high signal-to-noise ratio. The general arrangement of the SHPB set-up is given in Fig. 3. The set-up consists principally of a gun barrel, a 350 mm long striker bar (2024-T4 Al alloy), input and output bars, which remain elastic during the tests. The specimen is held in place between the two Hopkinson bars (see the inset in Fig. 3) by applying a small pre-compression load with turning of the head of a support block. As in the static tests, lubricant (MoS$_2$) is applied to the bar/specimen interfaces to reduce the frictional effects. When the input bar is impacted with the striker bar launched through the gun barrel, a compressive strain pulse ($\varepsilon_r$) is generated in the input bar and travels towards the specimen. At the bar/specimen interface, because of the impedance mismatch, part of the strain pulse is reflected back into the input bar ($\varepsilon_r$) and the

![Fig. 2 Typical static compressive stress-strain loops of four different plastics](image)

![Fig. 3 Schematic diagram of conventional split Hopkinson pressure bar set-up (recording system not shown)](image)
Fig. 4 Lagrangian diagram for compressive split Hopkinson bar test

remaining part is transmitted through the specimen into the output bar ($\varepsilon_r$). A Lagrangian $x$-$t$ diagram illustrating the details of the strain pulse propagation in the Hopkinson bars is given in Fig. 4. Note that in the impact testing of the plastics, the duration time of the reflected and transmitted strain pulses commonly becomes much longer than that of the incident strain pulse. This is due to a long retardation time [18] of the plastics. The incident, reflected and transmitted strain pulses are then recorded with two pairs of strain gages (KYOWA: KSP-2-120-E4) mounted on the Hopkinson bars. The output signals from the strain gages are fed through a bridge circuit into a 10-bit digital storage oscilloscope (IWATSU: DS-9121), where the signals are digitized and stored at a sampling time of 1 µs/word. The digitized data are then transferred to a 32-bit personal computer (NEC: PC-9821Xb) for data processing.

By applying the elementary one-dimensional elastic wave propagation theory, we can determine the nominal strain $\varepsilon(t)$, strain rate $\dot{\varepsilon}(t)$ and stress $\sigma(t)$ in the specimen as [19]

$$\varepsilon(t) = \frac{u_i(t) - u_s(t)}{l} = \frac{2c_s}{l} \int_0^t [\varepsilon_i(t') - \varepsilon_s(t')]dt'$$

(1)

$$\dot{\varepsilon}(t) = \frac{\dot{u}_i(t) - \dot{u}_s(t)}{l} = \frac{2c_s}{l} [\varepsilon_i(t) - \varepsilon_s(t)]$$

(2)

$$\sigma(t) = \frac{P_2(t)}{A_s} = \frac{AE}{A_s} \varepsilon_i(t)$$

(3)

under the assumption of dynamic force equilibrium ($P_1(t) = P_2(t)$; see the inset in Fig. 3) across the specimen. Here $c_s$ denotes the longitudinal elastic wave velocity (= 5130 m/s) in the Hopkinson bars; $\varepsilon_i(t)$ and $\varepsilon_s(t)$ are the time-resolved incident and transmitted strain pulses; $t$ is the time; $A$ and $E$ denote the cross-sectional area and Young's modulus (= 73 GPa) of the Al alloy Hopkinson bars; $l$ and $A_s$ denote the length (or thickness) and cross-sectional area of the specimen. Eliminating time $t$ through Eqs. (1) to (3) yields the nominal (or engineering) compressive stress-strain and strain rate-strain relations. The compressive stress and strain are assumed to be positive in this work.

3. Results and Discussion

A number of the SHPB tests were conducted at room temperature. Typical oscilloscope records from the SHPB test on PC are indicated in Fig. 5. The top trace gives the incident and reflected strain pulses ($\varepsilon_i$ and $\varepsilon_r$), and the bottom trace gives the transmitted strain pulse ($\varepsilon_s$). The resulting axial stress histories at the front and back ends of the specimen are shown in Fig. 6. The nearly overlapping histories clearly indicate that dynamic stress equilibrium is achieved in the specimen over the entire loading duration. Figure 7 presents the resulting dynamic stress-strain loop and strain rate-strain relations in compression. The strain

Fig. 5 Oscilloscope traces from split Hopkinson pressure bar test on PC ($V_s = 9.3$ m/s)
crosshead speed of 100 mm/min. It is observed that the initial slope (or Young's modulus $E$) and the area within the loop increase greatly with increasing strain rate. In an effort to evaluate the effects of strain rate on the overall compressive properties, the measured values for the Young's modulus, flow stress at 2.5% strain and dissipation energy are plotted in Figs. 9 to 11, respectively, as functions of the average strain rate. The dissipation energy is given as the area enclosed by the loop. As can be seen from Figs. 9 to 11, Young's modulus, the flow stress at 2.5% strain and the dissipation energy increase
significantly with increasing strain rate for all plastics. It is found that all plastics exhibit inherent dynamic viscoelastic characteristics. The dissipation energy is mostly converted to heat during high rate deformation, which causes the adiabatic temperature rise within the specimen. In an attempt to quantitatively evaluate the rate dependence of the flow stress at 2.5% strain, two different strain-rate sensitivity parameters [20] are introduced. The two parameters estimated for a constant strain of 2.5% for all plastics are summarized in Table 2. It is clearly seen that the flow stress of PA-66 displays the highest positive strain-rate sensitivity. A similar trend in the values for the strain-rate sensitivity parameter \( \beta \) is observed between the present work and Ref. [9].

Figures 12 and 13 show, respectively, the picture of typical static and impact compression specimens of PC before and after testing, indicating that the residual strains in both specimens are completely recovered to zero.

4. Conclusions
The strain-rate dependence of the uniaxial compressive stress-strain loops of the four commercial engineering
plastics has been investigated using both the standard SHPB and the Instron 5500R testing machine. From the present experimental work, we can draw the following conclusions:

1. All plastics exhibit intrinsic dynamic viscoelasticity and a high elastic aftereffect following complete unloading.

2. Young’s modulus, the flow stress at 2.5% strain and the dissipation energy for all plastics increase greatly with increasing strain rate.

3. Of the four plastics, PA-66 shows the highest strain-rate sensitivity of the flow stress.

4. Of the four plastics, PC exhibits the highest strain-rate sensitivity of the energy absorption capability.

Fig. 12 Picture of static (low strain-rate) compression specimens of PC before and after testing

Fig. 13 Picture of impact compression specimens of PC before and after testing

References