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Dynamic Mechanical Behaviour of Polymer Materials

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Abstract

In this chapter, we present the current research program of dynamic mechanical behaviour of polymer materials. Polymers typically have low strength, stiffness and wave impedance, making it challenging to obtain accurate stress-strain relations at high strain rates. The challenges in split Hopkinson bar testing technique modified for characterizing the mechanical response of polymers under high-rate loading are introduced first. Then, various representative polymers are reviewed for illustrating the strain-rate dependencies of mechanical data and their constitutive modellings.

Keywords: polymer, strain rate, dynamic mechanical response

1. Introduction

Exploring the potentials of advanced materials and structures for serving in extreme conditions has been a hot research topic for decades [1–5]. Materials and material technologies can be tailored nowadays for the applications in structural engineering. In recent years, impact-resistant devices and structures have received considerable attention because of the engineering requirements of safety and security. They require the dedicated design concepts and optimized material properties. Most materials currently available lead to the increase in weight and/or volume of structures and devices for meeting the impact-resistant requirements. In many cases, these increases are unacceptable in structure design. For solving this problem, the trend in materials is towards weight reduction and strength increase at reasonable costs. Material technologies are enablers to meet these requirements. They provide the potential to design advanced materials with high special strength (strength-to-weight ratio) and toughness for the applications in dynamic events.

Polymer materials have become a widely concerned research focus in extreme conditions because of their outstanding performances, such as impact resistance, rate dependency, corrosion resistance, low density, easy moulding and so on. Even more, in some engineering applications, they show outstanding advantages and replace the traditional metals and non-metallic materials [1, 2].

Therefore, understanding the dynamic mechanical behaviour of polymers is necessary. Especially, the investigations of polymers in explosion, shock, collision and other related mechanical behaviour under impact loading have both theoretical and practical significances. In this chapter, the current research program of dynamic mechanical behaviour of various representative polymers is presented.

2. Characterization technology

Due to the action of high strain-rate loading [6–10], dynamic mechanical response of materials is different from that under static loading. Characterizing dynamic mechanical behaviour is full of interest for material applications in impact events. For polymers, because of their low wave impedance, a longer time is needed to reach the dynamic stress equilibrium during split Hopkinson bar (SHB) test [11, 12], which produces more difficulties in high-rate mechanical experiments.

In order to reduce the difference in wave impedance, the viscoelastic impact bar is used in SHB test [13]. However, the viscoelastic bar itself has a strain-rate sensitivity, which easily results in the dispersion and attenuation of stress wave during the travelling in bar [14]. Aluminium alloy bar seems to be effective for testing polymer materials, thanks to the match of wave impedance and its lower strain-rate sensitivity. For meeting the conditions of constant strain rate and dynamic stress equilibrium, it is necessary to accurately design the shape of incident pulse [15]. A pulse-shaping technique is applied to meet these requirements, which, in general, places a wafer at the end of incident bar. The wafer material can be copper. The advantage of this pulse-shaping technique is to reduce the oscillation of incident wave. By selecting the appropriate specimen shape and size, the constant strain-rate loading with uniform stress in specimen can be realized [8, 16, 17]. Besides, low wave impedance material in SHB experiment will make the transmitter signal weak, which results in a small difference between the incident signal and reflected signal. The semiconductor strain gauge is more sensitive [18], which can be used to detect the weak signal. So, it can be used in the SHB experiment to test the soft polymer materials.

Moreover, it is necessary to clarify the calculating methods of stress, strain and strain rate of the tested specimen from the signals recorded by strain gages in an SHB test. They are based on the assumption of one-dimensional stress wave theory. Two long slender elastic bars in SHB apparatus are shown in **Figure 1**, which sandwich a short cylindrical specimen in between them.

When the striker bar impacts the end of the incident bar, a compressive stress wave is produced that immediately begins to travel along the bar towards the specimen. Upon arriving at the specimen, the compressive stress wave partially reflects back towards the impact end of the incident bar. The remainder of the compressive stress wave transmits through the specimen

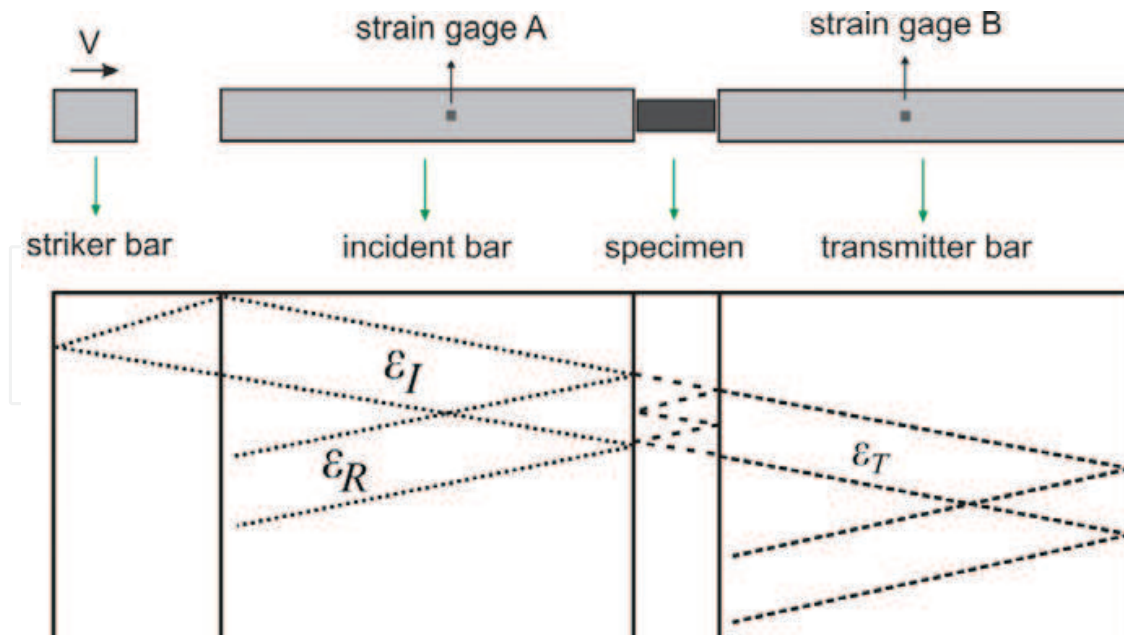


Figure 1. Schematic representation of the elastic waves travelling in a split Hopkinson bar (SHB) apparatus [8].

and enters into the transmitter bar, resulting in the deformation of the tested specimen [8]. Herein, the acoustic impedance of the specimen should be lower than the bar's impedance. The reflected pulse is a tensional wave, whereas the transmitted pulse remains in compression. The stress wave-induced strain histories of the incident bar and transmitter bar are recorded by strain gages A and B, respectively.

As long as the stress in the two bars remains under their elastic limits, specimen stress, strain and strain rate may be calculated from the recorded strain histories of the incident bar and transmitter bar. Herein, two important strain histories are needed to be identified, which are the reflected wave and the transmitted wave through the specimen. Kolsky [7, 8] applied one-dimensional stress wave theory to develop the following relation for calculating the specimen's engineering stress, $\sigma_S(t)$:

$$\sigma_S(t) = E \frac{A_0}{A_S} \varepsilon_T(t) \quad (1)$$

in which E is the transmitter bar's elastic modulus; A_0 is the transmitter bar's cross-sectional area; A_S is the specimen's cross-sectional area before loading and $\varepsilon_T(t)$ is the transmitted strain history.

The specimen strain rate, $\dot{\varepsilon}_S(t)$ can be calculated as:

$$\dot{\varepsilon}_S(t) = \frac{d\varepsilon_S(t)}{dt} = \frac{-2C_0}{L} \varepsilon_R(t) \quad (2)$$

in which $\varepsilon_R(t)$ is the reflected strain history; L is the specimen length prior to impact and C_0 is the wave velocity in the incident bar. The reflected wave represents the strain-rate history in the specimen. So, the flat plateau in the reflected signal corresponds to a nearly constant rate of the specimen deformation during dynamic loading. The wave velocity in the incident bar, C_0 , can be calculated from the theory of elementary vibrations, as below:

$$C_0 = \sqrt{E/\rho} \quad (3)$$

in which E and ρ are the incident bar's elastic modulus and density, respectively. Equation (2) can be integrated with time to attain the specimen's engineering strain history, $\varepsilon_S(t)$, as below:

$$\varepsilon_S(t) = \frac{-2C_0}{L} \int_0^t \varepsilon_R(t) \quad (4)$$

Thus, the data of specimen engineering stress, strain and strain rate can be derived from the recorded strain gage signals in an SHB experiment.

However, a uniform deformation of the specimen during SHB experiment should be maintained so that the experimental results can be clearly documented and interpreted for characterizing the dynamic stress-strain relation of a material.

Dynamic stress equilibrium is important for the validity of an SHB experiment. The stress in the specimen can be expressed in terms of the force exerted on each end surface of the specimen. When the specimen is sandwiched in between the incident bar and transmitter bar under dynamic compressive loading, the forces, $F_1(t)$ and $F_2(t)$, are imposed on the specimen with a diameter of D_S and a length of L_S . The average force, F_{avg} , applied on the specimen can be given as:

$$F_{avg}(t) = \frac{F_1(t) + F_2(t)}{2} \quad (5)$$

Whereas, the average engineering stress on the tested cylindrical specimen is:

$$\sigma_{avg}(t) = \frac{F_{avg}(t)}{\frac{1}{4}\pi D_S^2} \quad (6)$$

Herein, the forces, $F_1(t)$ and $F_2(t)$ applied on the specimen end surfaces are from the incident bar and transmitter bar, respectively. These two forces can be expressed in terms of elastic strains in the incident bar and transmitter bar, respectively, and can be calculated from the incident, reflected and transmitted signals, as below:

$$F_1(t) = E[\varepsilon_I(t) + \varepsilon_R(t)] \frac{\pi D_{bar}^2}{4} \quad (7)$$

$$F_2(t) = E\varepsilon_T(t) \frac{\pi D_{bar}^2}{4} \quad (8)$$

in which D_{bar} is the diameter of the incident bar (and the transmitter bar) and $\varepsilon_I(t)$, $\varepsilon_R(t)$ and $\varepsilon_T(t)$ are the strain histories of the incident, reflected and transmitted waves, respectively. For a specimen under high-speed loading, the dynamic stress equilibrium should be met for a constant strain rate, which means that $F_1(t)$ should be equal to $F_2(t)$, as below:

$$F_1(t) = F_2(t) \quad (9)$$

However, in a real SHB experiment, the deviation exists between these two force histories. In order to analyse and quantify the deviation, a criterion for stress equilibrium is employed to compare the forces (or stresses) exerted on the specimen end surfaces. Ravichandran and Subhash [19] introduced a parameter, $R(t)$, to evaluate the proximity to stress equilibrium in the specimen, as below:

$$R(t) = \left| \frac{\Delta\sigma(t)}{\sigma_{avg}(t)} \right| = \left| \frac{\Delta F(t)}{F_{avg}(t)} \right| = 2 \left| \frac{F_1(t) - F_2(t)}{F_1(t) + F_2(t)} \right| \quad (10)$$

in which, $\Delta\sigma(t)$ and $\Delta F(t)$ are the differences of these two stresses and forces applied on the specimen end surfaces, respectively. $\sigma_{avg}(t)$ and $F_{avg}(t)$ are the averages of these two stresses and forces, respectively (see Eqs. (5) and (6)). The specimen is assumed to be in dynamic stress equilibrium, when the value of $R(t)$ is less than 0.05 [8]. This general criterion has been employed extensively to evaluate the dynamic stress equilibrium process in SHB experiments.

By substituting Eqs. (7) and (8) into Eq. (10), the parameter $R(t)$ can be expressed by means of the relation between the incident, reflected and transmitted waves, as below:

$$R(t) = 2 \left| \frac{F_1(t) - F_2(t)}{F_1(t) + F_2(t)} \right| = 2 \left| \frac{\varepsilon_I(t) + \varepsilon_R(t) - \varepsilon_T(t)}{\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)} \right| \quad (11)$$

For a specimen under dynamic stress equilibrium, the forces applied on the specimen end surfaces can be expressed in terms of the two pressure bar strains, as expressed in Eqs. (7) and (8). Thus, according to Eq. (11), the following relation can be derived:

$$\varepsilon_I(t) + \varepsilon_R(t) = \varepsilon_T(t) \quad (12)$$

Therefore, by applying an assumption of the positive travelling harmonic wave and the equation of motion, the expressions for the specimen's engineering stress, strain and strain rate can be derived in terms of the two pressure bars' strains, as shown in Eqs. (1), (4) and (2), respectively. In turn, under dynamic stress equilibrium, Eqs. (1), (4) and (2) are qualified to be used for calculating the specimen's engineering stress, strain and strain rate.

Therefore, the SHB technology for dynamic compression and tension experiments has been introduced. It is a mature method and a commonly used apparatus to characterize accurately the dynamic mechanical properties of various materials in the strain rates ranging from 1000/s to 10,000/s [20].

In this chapter, in order to characterize the high strain-rate mechanical response of polymer materials, the SHB technique is selected as the experimental equipment. On the one hand, the SHB equipment can accurately derive the dynamic mechanical properties of material under high-speed loading. On the other hand, it can be well controlled under laboratory working conditions [20].

3. Various polymers for dynamic mechanical investigation

3.1. Rubber-like polymers

Rubber-like polymer has been used extensively as structural material of engineering components that are designed to resist impact, ranging from bus windows and eyeglasses to protective helmets and body armours. The choice of polymer materials for these applications has been made appealing by the relative low density and the transparency that are the characteristics of amorphous homopolymers. One of the studies on polymer materials focuses on the capability of absorbing dynamic strain energy and strain-rate dependency [1, 21–30]. Strain-rate dependency of the stress-strain behaviour of polymer materials has been well documented, where, in particular, yield stress is found to increase with the increasing strain rate. This feature of mechanical behaviour is highly relevant to engineering applications, when designing a polymer component required to resist an impact loading.

3.1.1. Polyurea

The thermoplastic elastomer polyurethane and the elastomeric thermoset polyurea are found to have new applications by increasing the survivability of structures under impact loading, including those encountered in blast and ballistic events. Yi et al. [31] studied the large deformation and rate-dependent stress-strain behaviour of polyurea and polyurethanes in dynamic compressive tests. A set of data was presented to quantify the rate-dependent behaviour of these materials from low strain rates ($<1/s$) to high strain rates ($>1000/s$), as shown in **Figure 2**.

The polyurea displayed a transition of deformation behaviour from rubber-like behaviour at low strain rates to leathery behaviour at high strain rates, whereas one of these three polyurethanes displayed a transition from rubber-like behaviour at low strain rates to glass-like behaviour at high strain rates. **Figure 2** presents the rate-dependent behaviour by means of the stress vs logarithm strain rate, taking the stress evaluated at a strain level of 0.15 and 0.30 for

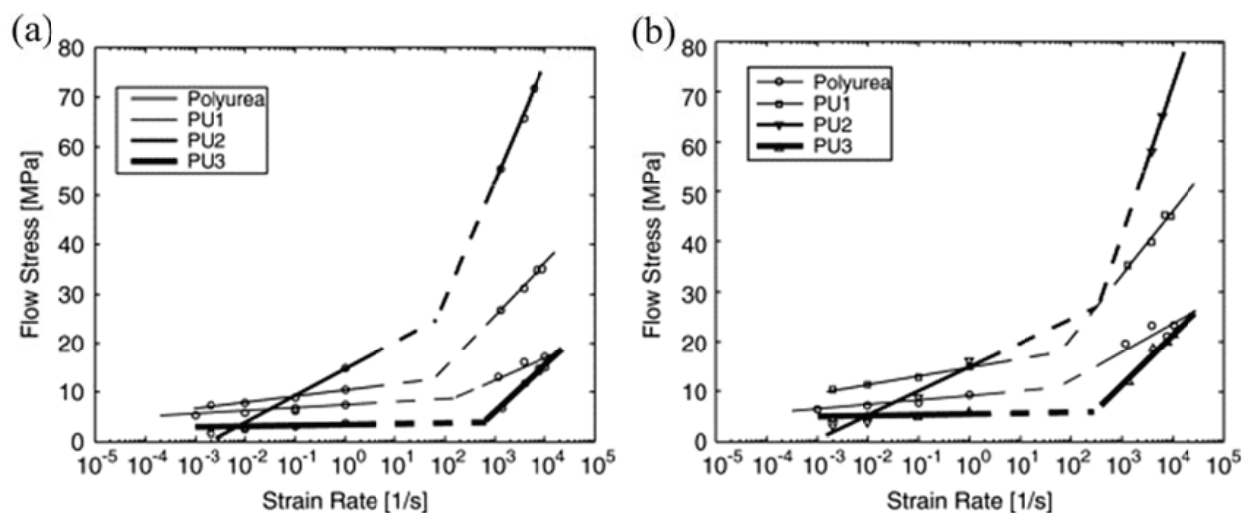


Figure 2. Flow stress vs strain rate relations of polyurea and three polyurethanes determined at the deformation strain of (a) 0.15 and (b) 0.30 [31].

Figure 2a and **b**, respectively. For both strain levels, the flow stress obviously demonstrated a close-to-linear dependency on the logarithm strain rate in both the high strain rate ($\geq 10^3/s$) and low strain rate ($\leq 10^0/s$) regions. So, mechanical behaviour, as illustrated by yield stress of the thermoplastic-elastomeric polyurethanes and elastomeric-thermoset polyureas, is strongly dependent on strain rate.

In addition, continuous investigation was conducted on the characterization of mechanical properties at very high strain rates under both dynamic compression and tension loadings [32]. The experimental results are shown in **Figure 3**. The uniaxial compression and tension data for polyurea are found to be consistent at the strain rates ranging from 0.001/s to 10,000/s, both of which increase with the increase in strain rate. Therefore, a strong dependency of flow stress on strain rate is clarified in the material of the thermoplastic-elastomeric polyurethane and elastomeric-thermoset polyurea, which is of particular interest when they play a role as a protective coating to enhance survivability of structures in high-rate loading events.

3.1.2. Polyurethane

Zhang et al. [33] studied the dynamic mechanical behaviour of a polyurethane used as an interlayer in a laminated windshield construction at various strain rates (0.001/s to 7000/s) and

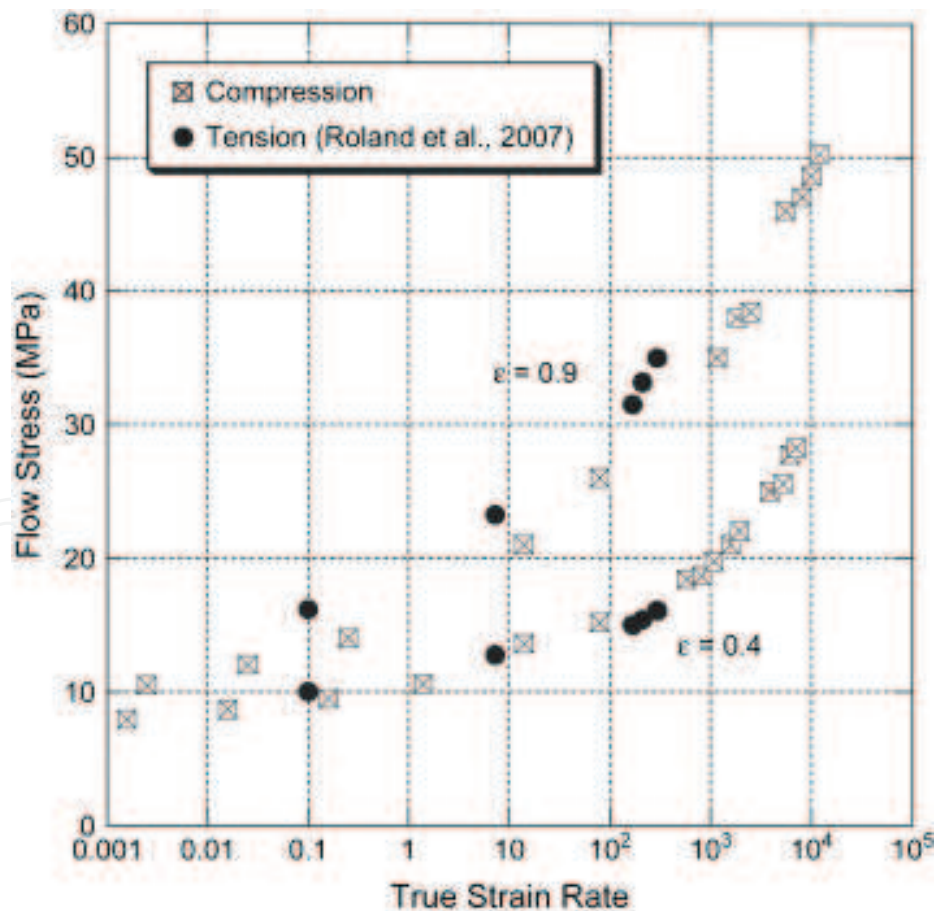


Figure 3. Stresses, taken at the true strain of 0.4 and 0.9, as a function of the true strain rate of the polyurea, where the value of the true strain rate used for each point is also taken at the true strain of 0.4 or 0.9 [32].

various temperatures (-40°C to 25°C). The research results reveal that the mechanical behaviour of polyurethane interlayer is dependent on temperature and strain rate. Under dynamic loading, the transition from “rubbery” to “glassy” is exhibited in the stress-strain curves at 240°C . In terms of the constitutive theory and experimental data, one-dimensional thermal-hyper-visco-elastic constitutive equation is recommended to characterize the compressive deformation response of polyurethane interlayer over a wide range of temperatures and strain rates.

Figure 4 shows the true stress-strain curves of polyurethane interlayer at different temperatures and at a certain strain rate. The temperature-dependent behaviour is clearly seen. When temperature decreases, the stress-strain curve goes up with the increase in yield stress, and the strain-hardening behaviour becomes remarkable. At high strain rates and at low temperature, the flow stress date exhibits an obvious increase. Under the quasi-static ($0.001/\text{s}$) loading, the stress-strain results illustrate a common phenomenological mechanical behaviour of soft materials revealed in compression experiment at a low strain rate. As the temperature decreases from -20°C to -40°C , the significant changes occur in stress-strain curves. A rubbery behaviour transits into

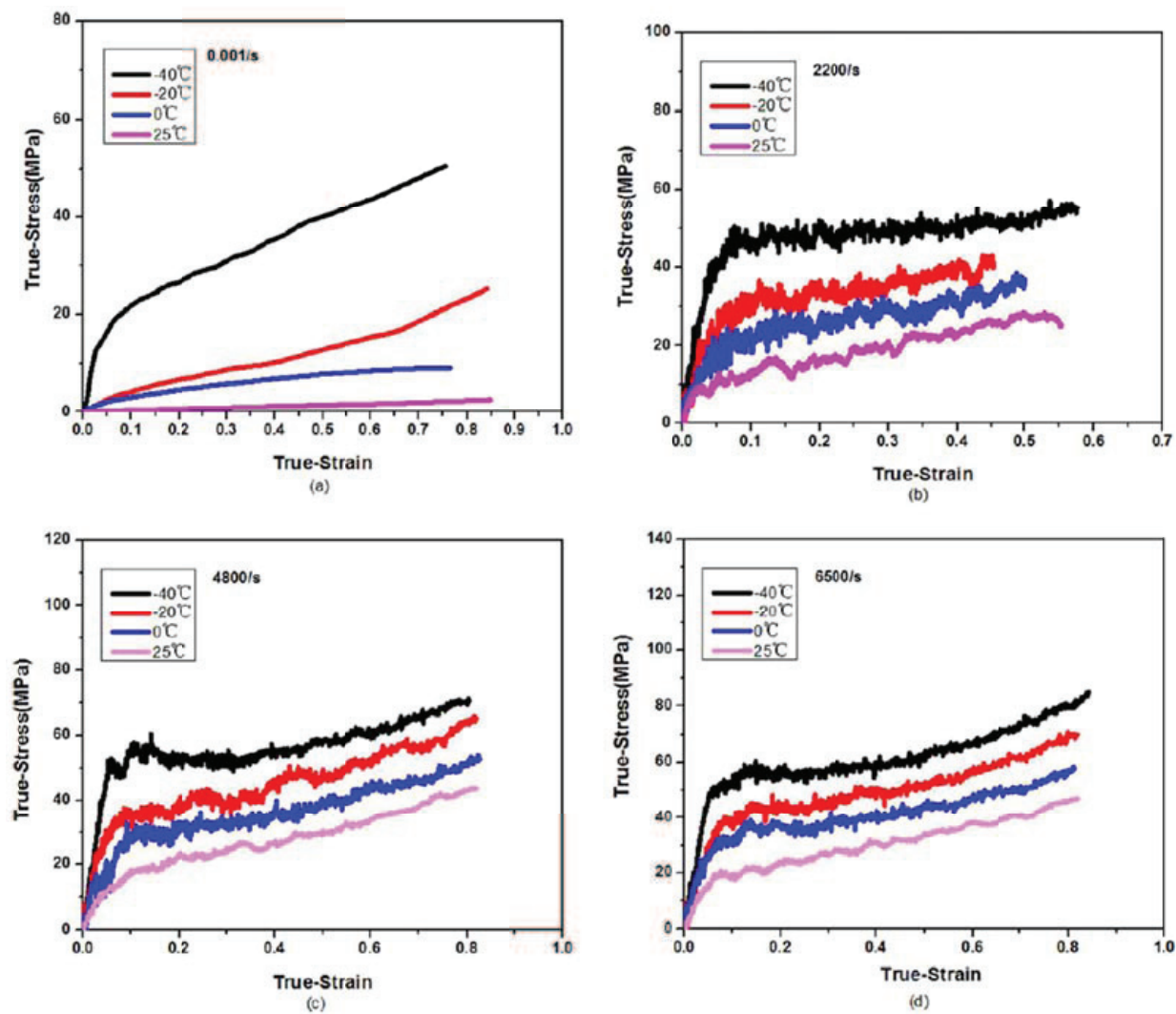


Figure 4. True stress-strain curves of the polyurethane interlayer: (a) $0.001/\text{s}$, (b) $2200/\text{s}$, (c) $4800/\text{s}$ and (d) $6500/\text{s}$ [33].

glassy behaviour of the mechanical response, which is in line with the mechanical behaviour of the rubber-like materials below and above glass transition temperature. The inherent reason can be the glass transition temperature of the polyurethane interlayer of around -58°C to -40°C .

Figure 5 shows the true stress-strain curves and the corresponding true strain rate-strain curves at a temperature of 25°C . The trend of strain rates seems to be relatively constant over the courses, which indicates that dynamic stress equilibrium is nearly stable. The uniaxial compressive stress-strain behaviour in the regime of high strain rate has a strong dependency of strain rate and temperature. At the same temperature, with the increase in strain rate, the flow stress increases and the strain hardening behaviour becomes more apparent.

3.1.3. Polyurethane elastomer

Fan et al. [34] developed a soft polyurethane elastomeric material for impact-resistant applications. Stress-strain relations, characterized by using a split Hopkinson tension bar, are derived to reveal the mechanical properties at different strain rate levels at room temperature, as shown in **Figure 6**. The stress-strain curves from multiple tests at comparable strain rates are similar and partially overlap, illustrating the good reproducibility of the experimental data. The dynamic stress-strain curves show a different behaviour, compared to quasi-static stress-strain plot at a strain rate of $0.01/\text{s}$. This difference has been also observed for other soft polymer materials [35, 36].

In statics, the initial stiffness of the soft polyurethane elastomeric polymer material is much negligible. While in dynamics, stiffness becomes significantly higher, and the length of the linear ascending branch increases with the increase in strain rate. Even though stress equilibrium is not

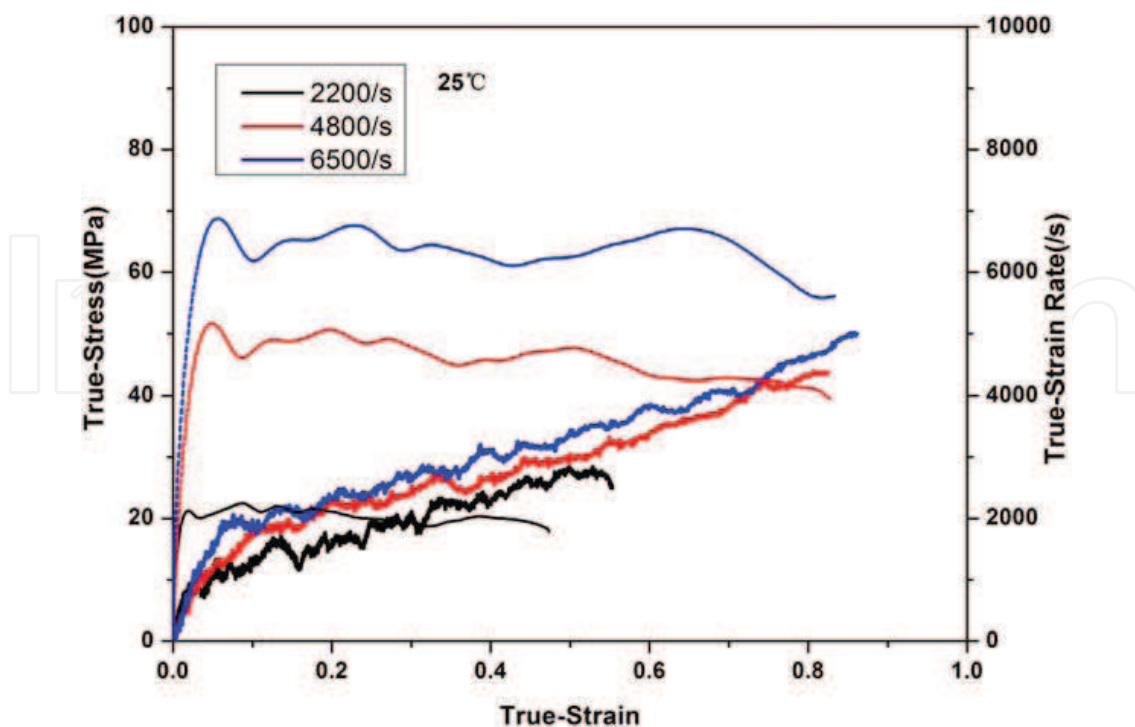


Figure 5. True stress-strain curves and the corresponding true strain rate-strain curves at a temperature of 25°C [33].

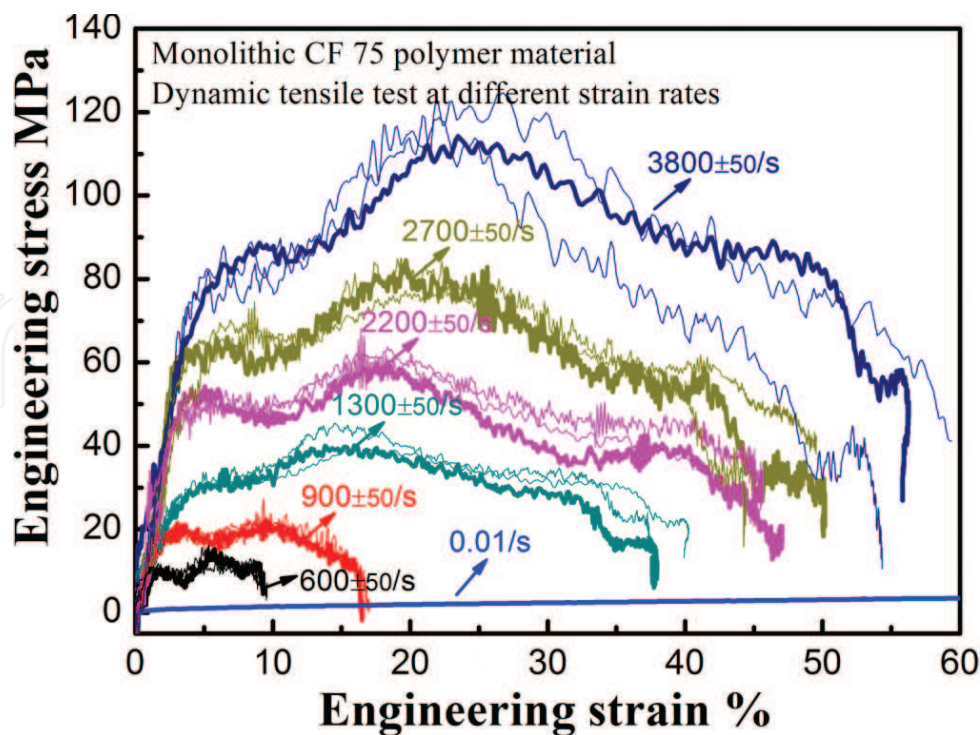


Figure 6. Representative engineering stress-strain plots of the soft polyurethane elastomeric polymer material under dynamic tension loading with three curves per selected strain rate level [34].

attained in the specimen at the beginning of the initial dynamic loading, a linear link of yielding point and origin point (0, 0) in the stress-strain curve can be conducted to roughly evaluate the dynamic tensile modulus, considering that material yielding occurs after dynamic stress equilibrium. The line slope is the tangent modulus, which can indicate the material stiffness at the corresponding strain rate. The relation between tangent modulus and strain rate is shown in **Figure 7**. By linearly fitting the curve of tangent modulus versus log strain rate, a log strain rate value of 2.65 or about 450/s strain rate is attained. It indicates that the strain rate of 450/s is the critical transition point at which mechanical response of the soft polyurethane elastomeric polymer material changes from a rubber-like behaviour at low strain rates to a glass-like behaviour at high strain rates at room temperature [31, 37].

3.2. Glass-like polymers

The development of glass-like polymer materials that are more impact- and ballistic-resistant has many possible applications ranging from military vehicle windows to civilian products. Two common kinds of organic glasses that are used in these engineering areas include the polycarbonate (PC) and polymethyl methacrylate (PMMA). These materials are transparent and lightweight compared with their inorganic counterparts, which is important especially in vehicle and personal protection applications. Each of these materials has a unique inherent mechanism by which energy is absorbed during impact. Polycarbonate, like other ductile materials, has the capability to absorb a large amount of energy through yielding and plasticity. For PMMA, the majority of energy absorption is due to the creation of new surface area during fracture. There is an obvious difference between their macroscopic failure mechanisms.

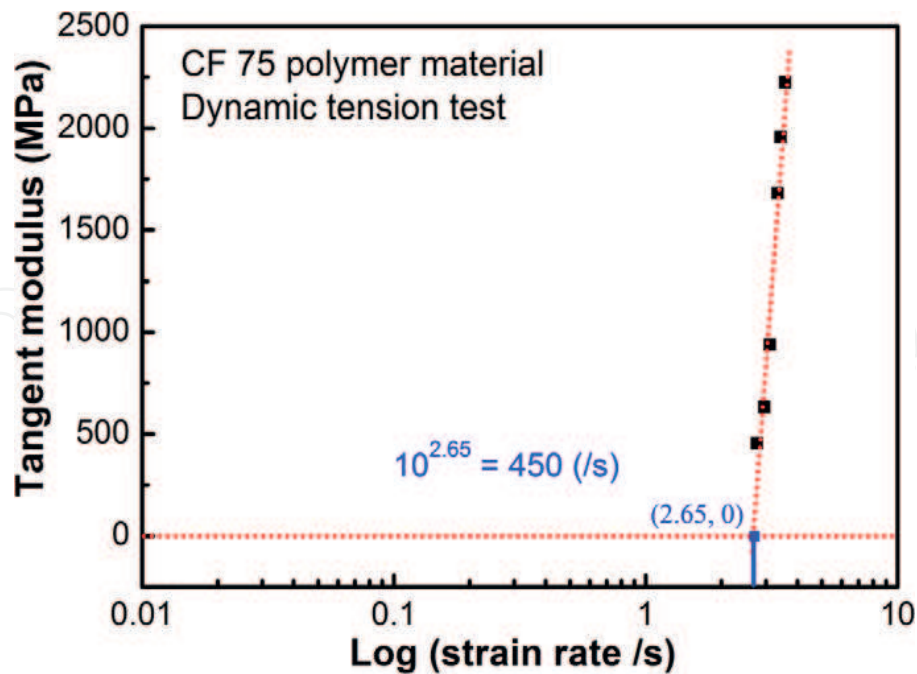


Figure 7. The relation of tangent modulus versus strain rate curve for determining the critical strain rate of the soft polyurethane elastomeric polymer material for the transition from a rubber-like behaviour at low strain rates to a glass-like behaviour at high strain rates at room temperature [34].

Failure in PC is relatively localized while PMMA is effective at delocalizing failure in the form of radial cracking and Hertzian cone fracture (during impact). Moreover, the glass-like polymers also have an obvious rate dependency of mechanical properties [1, 38, 39], which directly affects the dynamic strength and determines the structure design, application and reliability for safety and security.

3.2.1. Polymethyl methacrylate (PMMA)

As one of glass-like polymers, polymethyl methacrylate (PMMA) is reviewed for clarifying the dynamic mechanical behaviour [1]. A combined experimental and analytical method has been performed to investigate the mechanical behaviour of PMMA material at strain rates ranging from 10^{-4} /s to 10^4 /s. The relation of yield stress and strain rate is documented in **Figure 8**.

The yield stress was found to increase as a non-linear function with the logarithmic strain rate, displaying the strain-rate sensitivity. The mechanisms of the rate-dependent elastic-plastic deformation of PMMA material from low to high strain rates were also studied. A computational model was developed based on the concepts of both the Ree-Eyring yield theory and the viscoelastic theory, which indicates that intermolecular resistance to deformation may be decomposed into the contributions of different molecular processes, each with their own unique rate and temperature dependency. This model is probably suitable for two-component polymer materials.

Therefore, rate-dependent behaviour of polymer materials was revealed and mechanisms for impact resistance were also explored using the combined experimental and computational

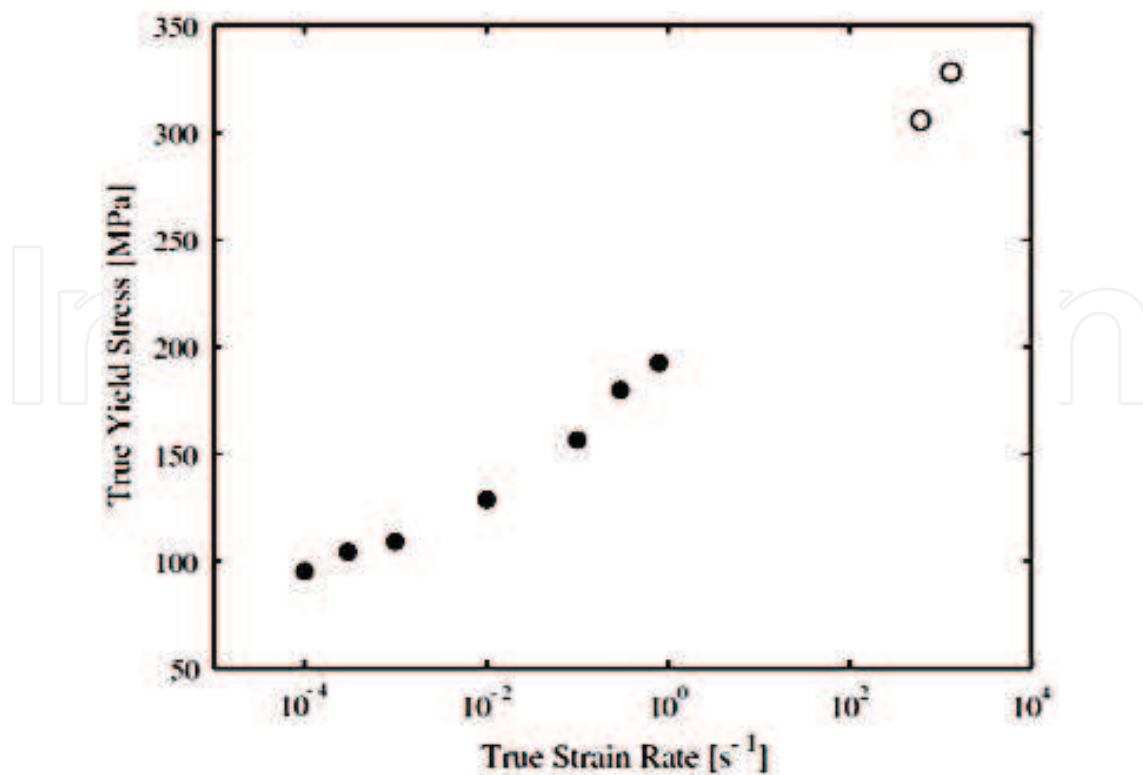


Figure 8. True yield stress of PMMA material as a function of true strain rate (logarithmic scale)—low to high strain rates [1].

methods. A concerted effort has been made to investigate and develop new polymer materials with improved characteristics for impact resistance and damage tolerance. Concerns regarding rate dependency and impact resistance of polymer materials are the basis for extensive research.

3.2.2. Polycarbonate (PC)

Dar et al. [39] studied the mechanical behaviour of polycarbonate (PC) polymer under the effect of various temperatures and strain rates. Mechanical characterizations are carried out through uniaxial compression and split Hopkinson pressure bar (SHPB) for revealing low and high strain rate response, respectively. Meanwhile, the experiments are performed for strain rates varying from 10⁻³/s to 10³/s and a temperature range of 213 K to 393 K. The experimental results reveal that the stress-strain behaviour of polycarbonates is much different at lower and higher strain rates. At higher strain rate, the polycarbonates yields at higher yield stress compared to that at low strain rate. At lower strain rate, yield stress increases with the increase in strain rate while it decreases significantly with the increase in temperature. Likewise, initial elastic modulus, yield and flow stress increase with the increase in strain rate, whereas decreases with the increase in temperature. Yield stress increases significantly for low temperature and higher strain rates.

SHPB tests were performed to determine the dynamic response of polycarbonate at strain rates varying from 1350/s to 9400/s. Dynamic tests were performed at five different strain rates, and the results in terms of true stress-strain curves are shown in **Figure 9**. The results show that yield stress increases with the increase in strain rate. The stress-strain curves show almost similar

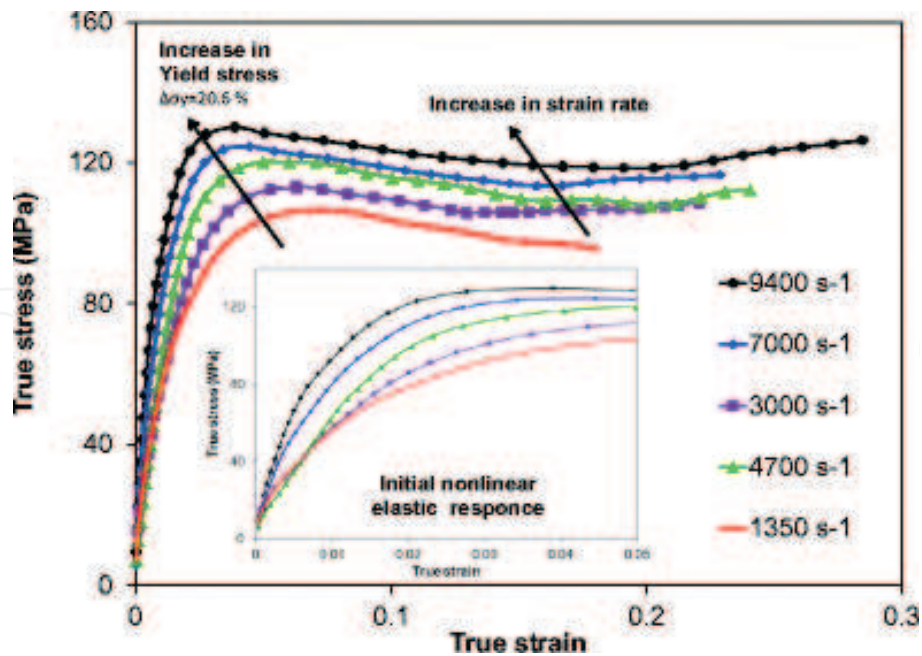


Figure 9. High strain rate stress-strain response of polycarbonate [39].

mechanical response in which initial nonlinear elastic behaviour was observed followed by subsequent yielding, strain softening and hardening. Yield stress changes significantly with the increase in strain rate. An increase of 20.6% in yield stress was calculated with strain rate increase from 1350 to 9400/s. At all strain rates, ductile response of polycarbonate was observed and ductile-brittle transition was not found.

Dynamic tests at a strain rate of 1350/s were also performed at three different temperatures and the results are shown in **Figure 10**. The change in yield stress is more significant in case of temperature than strain rate. The 43.4% decrease in yield stress with the increase in temperature from 233 K to 333 K is revealed.

Yield stress summarized at different strain rates and temperatures were plotted and a liner relationship was found between them as shown in **Figure 11**. A 0.69 MPa/K decrease in yield stress was observed between temperature variations of 233–333 K. Dynamic stress sensitivity $((\sigma_{dynamic} - \sigma_{static})/\sigma_{static})$ of polycarbonate is computed to be 128% which is significantly less than PMMA [40] showing that polycarbonate is not a highly strain rate-sensitive polymer. σ_{static} in this case is considered as quasi-static or very low strain rate stress.

3.2.3. Polymethylene diisocyanate (PMDI)

Song et al. [41] reported the dynamic mechanical response of three polymer foam materials made by rigid polymethylene diisocyanate (PMDI), varied in density (310 kg/m³, 410 kg/m³ and 550 kg/m³), at strain rates as high as 3000/s and at temperatures ranging from 219 K to 347 K. The effects of material density, strain rate and temperature on the compressive response of the polymer foam materials were determined. Compressive stress-strain curves of the three foam materials (with the densities of 310 kg/m³, 410 kg/m³ and 550 kg/m³) at various strain rates are shown in **Figure 12a–c**, respectively.

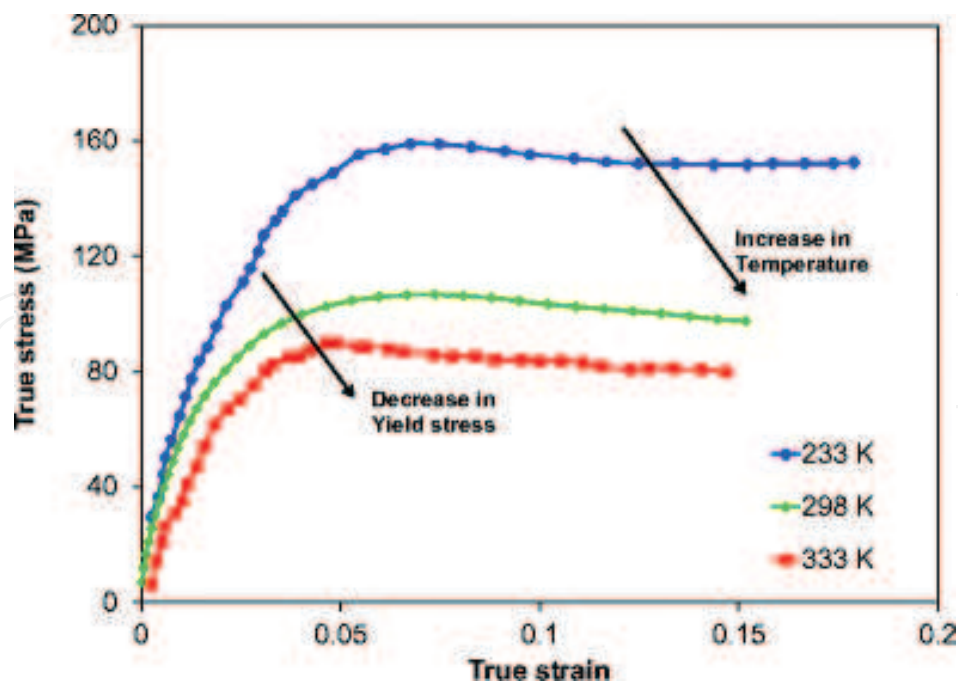


Figure 10. Effect of temperature on high strain rate stress-strain response [39].

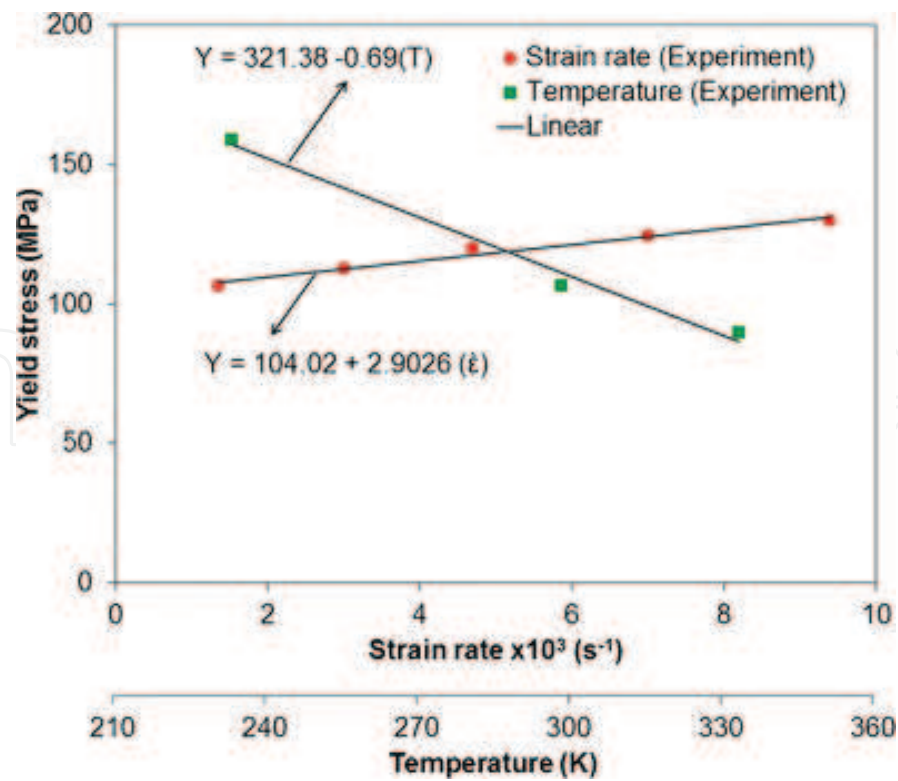


Figure 11. Effect of strain rate and temperature on yield stress [39].

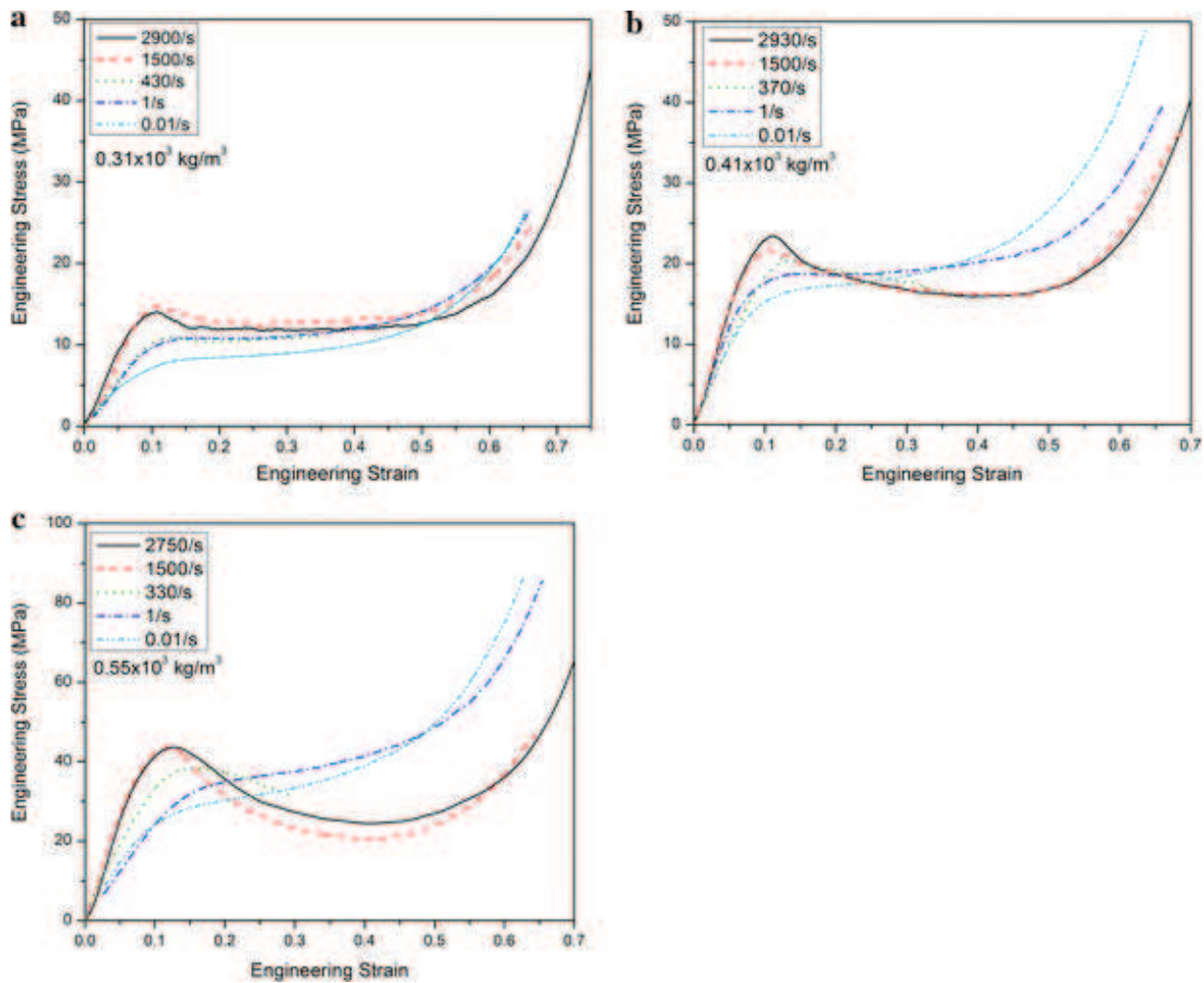


Figure 12. Compressive stress-strain curves at various strain rates for our three foam-material densities: (a) 310 kg/m^3 , (b) 410 kg/m^3 and (c) 550 kg/m^3 [41].

They are obtained at room temperature (295 K) and have a common characteristic: an initial linearly elastic deformation followed by a collapse process of cell structures. When all the cell structures were collapsed, the condensation initiates, as revealed by the increasing stress amplitude in the stress-strain response [42]. For each polymer foam material, this characteristic is varied slightly with strain rates, and the cell-structure collapse process has an apparent variation. Under quasi-static loading, the stress-strain curves exhibit a long stress plateau and/or slow strain-hardening behaviour after yielding. This stress plateau indicates the plastic buckling of cell structures. However, under dynamic loading, stress drops from the peak date after yielding, causing the formation of N-shaped stress-strain curves. The stress drop is caused by the sudden collapse of cell structures under high strain-rate loading. So, the deformation and damage mechanisms are influenced by the strain rates in the polymer foam material.

Yield stress is also found to be dependent on strain rate. **Figure 13** shows the details of the increase in yield stress with strain rate for these three polymer foam materials. The yield strength of the three foam materials linearly increases with the logarithm of strain rate, as

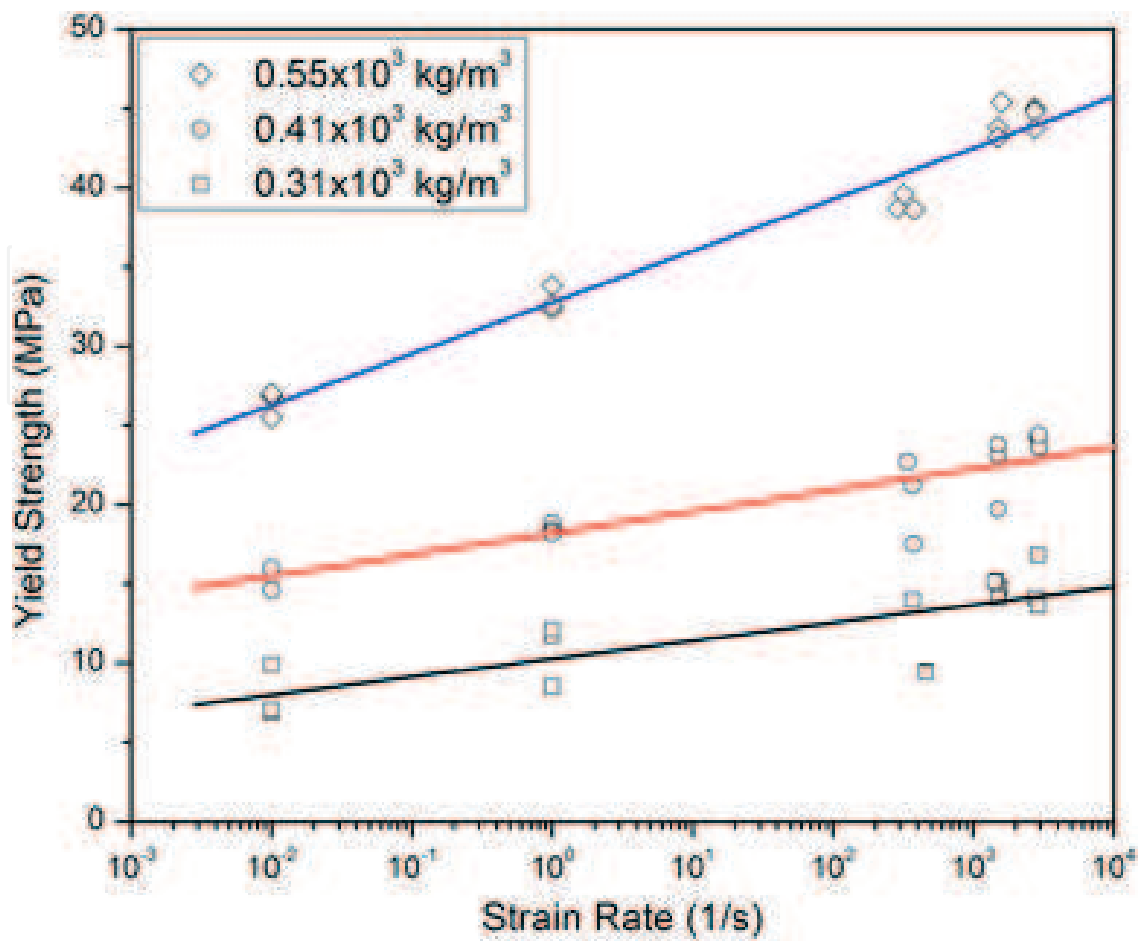


Figure 13. Strain-rate sensitivities of the three polymer foam materials with different densities [41].

shown by equation: $\sigma_y = A + B \log(\epsilon' / \epsilon'_0)$, wherein A and B are constant data, and ϵ'_0 is the reference strain rate. The constant B is the slope of the solid line, which represents the strain-rate sensitivity of yield stress. The two parallel lines at the bottom of **Figure 13** imply that the strain-rate sensitivities of the 310 kg/m³ and 410 kg/m³ polymer foam materials are nearly equal. Both are lower than that of the 550 kg/m³ polymer foam material.

4. Conclusion

In this chapter, the characterization method of mechanical response of polymer materials under high strain-rate loading is firstly introduced. Then, two kinds of polymer materials, rubber-like and glass-like, are reviewed to illustrate their dynamic mechanical response. Herein, three polymers are presented as the representatives of each kind of polymer materials. The rate-dependent mechanical data are given and the influence of temperature is also clarified. These knowledge outputs not only guide the research of developing new impact-resistant polymer materials, but also support the protection engineering of applying polymer materials in dynamic events.

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References

- [1] Mulliken A, Boyce MC. Mechanics of the rate-dependent elastic-plastic deformation of glassy polymers from low to high strain rates. *International Journal of Solids and Structures*. 2006;**43**(5):1331–1356
- [2] Richeton J, Ahzi S, Vecchio KS, Jiang FC, Adharapurapu RR. Influence of temperature and strain rate on the mechanical behaviour of three amorphous polymers: Characterization and modeling of the compressive yield stress. *International Journal of Solids and Structures*. 2006;**43**(7–8):2318–2335
- [3] Roland CM, Twigg JN, Vu Y, Mott PH. High strain rate mechanical behaviour of polyuria. *Polymer*. 2007;**48**(2):574–578
- [4] Naik NK, Pandya KS, Kavala VR, Zhang W, Koratkar NA. High-strain rate compressive behaviour of multi-walled carbon nanotube dispersed thermoset epoxy resin. *Journal of Composite Materials*. 2015;**49**(8):903–910
- [5] Deshpande VS, Fleck NA. High strain rate compressive behaviour of aluminium alloy foams. *International Journal of Impact Engineering*. 2000;**24**(3):277–298
- [6] Kolsky H. An investigation of the mechanical properties of materials at very high rates of loading. *Proceedings of the Physical Society (London)*. 1949;**62**:676–700
- [7] Grey GT III. Classic Split-Hopkinson pressure bar testing. In: *ASM Handbook: Mechanical Testing and Evaluation*. Metals Handbook. American Society for Metals, Materials Park. Vol. 8. 2000. pp. 462–476

- [8] Chen W, Song B. Split Hopkinson (Kolsky) Bar: Design, Testing and Applications. Springer, New York Dordrecht Heidelberg London. 2011
- [9] Tay TE, Ang HG, Shim VPW. An empirical strain rate-dependent constitutive relationship for glass-fibre reinforced epoxy and pure epoxy. *Composite Structures*. 1995;**33**:201–210
- [10] Yang LM, Shim VPW, Lim CT. A visco-hyperelastic approach to modeling the constitutive behaviour of rubber. *International Journal of Impact Engineering*. 2000;**24**: 545–560
- [11] Gray GT, Blumenthal WR. Split Hopkinson pressure bar testing of soft materials. In: ASM Handbook: Mechanical Testing and Evaluation. Metals Handbook. American Society for Metals, Materials Park. Vol. 8. 2000. pp. 488–496
- [12] Yin ZN, Wang TJ. Deformation of PC/ABS alloys at elevated temperatures and high strain rates. *Materials Science and Engineering: A*. 2008;**494**(1):304–313
- [13] Bouix R, Viot P, Lataillade JL. Polypropylene foam behaviour under dynamic loadings: Strain rate, density and microstructure effects. *International Journal of Impact Engineering*. 2009;**36**(2):329–342
- [14] Aleyaasiin M, Harrigan JJ. Wave dispersion and attenuation in viscoelastic polymeric bars: Analysing the effect of lateral inertia. *International Journal of Mechanical Sciences*. 2010;**52**:754–757
- [15] Lee OS, Cho KS, Kim SH. Dynamic deformation behaviour of soft material using SHPB technique and pulse shaper. *International Journal of Modern Physics*. 2006;**20**(25–27): 3751–3756
- [16] Rodríguez J, Cortés R, Martínez MA. Numerical study of the specimen size effect in the split Hopkinson pressure bar tests. *Journal of Materials Science*. 1995;**30**(18):4720–4725
- [17] El-Habak AMA. Compressive resistance of unidirectional GFRP under high rate of loading. *Journal of Composites Technology and Research*. 1993;**15**(4):311–317
- [18] Wang BZ, Hu SS, Zhou XR. Research of dynamic mechanical behaviour and constitutive model of rubber under different temperatures. *Journal of Experimental Mechanics*. 2007;**22**(1):1–6
- [19] Ravichandran G, Subhash G. Critical appraisal of limiting strain rates for compression testing of ceramics in a split Hopkinson pressure bar. *Journal of the American Ceramic Society*. 1994;**77**(1):263–267
- [20] Fan JT. Dynamic response of a polymer and polymer composite system: Experimental studies [PhD thesis]. Delft, The Netherlands: Delft University of Technology; 2015
- [21] Balieu R, Lauro F, Bennani B, Delille R, Matsumoto T, Mottola E. A fully coupled elastoviscoplastic damage model at finite strains for mineral filled semi-crystalline polymer. *International Journal of Plasticity*. 2013;**51**:241–270

- [22] Raman SN, Ngo T, Lu J, Mendis P. Experimental investigation on the tensile behaviour of polyurea at high strain rates. *Materials & Design*. 2013;**50**:124–129
- [23] Plaseied A, Fatemi A. Strain rate and temperature effects on tensile properties and their representation in deformation modeling of vinyl ester polymer. *International Journal of Polymeric Materials*. 2008;**57**(5):463–479
- [24] Daivis PJ, Matin ML, Todd BD. Nonlinear shear and elongational rheology of model polymer melts at low strain rates. *Journal of Non-Newtonian Fluid Mechanics*. 2007;**147**(1–2):35–44
- [25] Yu Q, Selvadurai APS. Mechanics of a rate-dependent polymer network. *Philosophical Magazine*. 2007;**87**(24):3519–3530
- [26] Hizoum K, Remond Y, Bahlouli N, Oshmyan V, Patlazhan S, Ahzi S. Nonlinear strain rate dependency and unloading behaviour of semi-crystalline polymers. *Oil & Gas Science and Technology*. 2006;**61**(6):743–749
- [27] Perkins TT, Smith DE, Chu S. Single polymer dynamics in an elongational flow. *Science*. 1997;**276**(5321):2016–2021
- [28] Smith DE, Chu S. Response of flexible polymers to a sudden elongational flow. *Science*. 1998;**281**(5381):1335–1340
- [29] Mead DW, Larson RG, Doi M. A molecular theory for fast flows of entangled polymers. *Macromolecules*. 1998;**31**(22):7895–7914
- [30] Arruda EM, Boyce MC, Jayachandran R. Effects of strain rate, temperature and thermomechanical coupling on the finite strain deformation of glassy polymers. *Mechanics of Materials*. 1995;**19**(2–3):193–212
- [31] Yi J, Boyce MC, Lee GF, Balizer E. Large deformation rate-dependent stress-strain behaviour of polyuria and polyurethanes. *Polymer*. 2006;**47**(1):319–329
- [32] Sarva SS, Deschanel S, Boyce MC, Chen WN. Stress-strain behaviour of a polyurea and a polyurethane from low to high strain rates. *Polymer*. 2006;**48**(8):2208–2213
- [33] Zhang L, Yao X, Zang S, Gu Y. Temperature- and strain rate-dependent constitutive modeling of the large deformation behaviour of a transparent polyurethane interlayer. *Polymer Engineering & Science*. 2014;**55**(8):1864–1872
- [34] Fan JT, Weerheijm J, Sluys LJ. High-strain-rate tensile mechanical response of a polyurethane elastomeric material. *Polymer*. 2015;**65**:72–80
- [35] Yang JH, Zhang Y, Zhang YX. Brittle-ductile transition of PP/POE blends in both impact and high speed tensile tests. *Polymer*. 2003;**44**(17):5047–5052
- [36] Song B, Chen WN, Liu ZS, Erhan SZ. Compressive properties of soybean oil-based polymers at quasi-static and dynamic strain rates. *Journal of Applied Polymer Science*. 2006;**99**(5):2759–2770

- [37] Kendall MJ, Siviour CR. Rate dependence of poly(vinyl chloride), the effects of plasticizer and time-temperature superposition. *Proceedings of the Royal Society A*. 2014;**470**(2167): 20140012
- [38] Acharya S, Mukhopadhyay AK. High strain rate compressive behaviour of PMMA. *Polymer Bulletin*. 2014;**71**(1):133–149
- [39] Dar UA, Zhang WH, Xu YJ, et al. Thermal and strain rate sensitive compressive behaviour of polycarbonate polymer—experimental and constitutive analysis. *Journal of Polymer Research*. 2014;**21**(8):1–10
- [40] Lee OS, Kim MS. Dynamic material property characterization by using split Hopkinson pressure bar (SHPB) technique. *Nuclear Engineering and Design*. 2003;**226**(2):119–125
- [41] Song B, Lu WY, Chul JS, et al. The effects of strain rate, density, and temperature on the mechanical properties of polymethylene diisocyanate (PMDI)-based rigid polyurethane foams during compression. *Journal of Materials Science*. 2009;**44**(2):351–357
- [42] Gibson LJ, Ashby MF. *Cellular Solids, Structure and Properties*. 2nd ed. Cambridge: Cambridge University Press; 1999