Constitutive Modeling of Army Face Shields

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Polycarbonate (PC) is used for face-shield applications because of its good optical properties and its high impact-resistance characteristics. The US Army is seeking to better understand the thermo-mechanical properties of PC for its use in transparent armor applications. In collaboration with Army Research Laboratory (ARL) researchers, we have started developing a PC constitutive model. Our goal is to use ARL-measured experimental properties supplemented by published experimental results to construct an improved constitutive model for PC and filled-PC composites.

An amorphous polymer, PC is glassy below temperatures of approximately 423 K. Moy et al. [1] have determined the PC yield stress and obtained stress-strain curves for rates between 10^{-5} to 10^{3} s^{-1}. The fracture properties and thermal heating of PC have been studied by Bjerke et al. [2]. Polycarbonate [2] was investigated in the glassy phase, and consequently strength loss occurred primarily by brittle failure. We will rely on the work of Ref. 1 and 2 in our model development. Molecular cooperativity theory is used to construct a rate- and pressure-dependent flow stress model. We incorporated viscoelasticity into our model by using ARL Dynamic Mechanical Analysis (DMA) data. This data can be used to determine the rate- and temperature-dependent shear relaxation function.

We developed an equation-of-state (EOS) model to handle the bulk response. To that end, we constructed the Gibbs free energy $G(P,T)$ as a function of pressure and temperature. The associated derivatives of $G(P,T)$ with respect to P and T then determine the complete thermodynamic properties of PC. We used the specific volume measurements of Zoller [3] and the heat capacity measurements of Cheng and Wunderlich [4] to construct $G(P,T)$.

Our EOS captures the behavior of specific volume (Fig. 1) and heat capacity (Fig. 2). (Note that only the zero pressure heat capacity data are measured). In Fig. 3, our predicted bulk modulus is shown. Figure 4 shows the stress-strain data of [1] and our theoretical stress-strain curves; the comparison is excellent. In future work we will attempt to implement glassy polymer damage behavior into our model. In this way we can begin to model the PC face shields as they are subjected to projectile impacts of various speeds.

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[1] P. Moy, et al., "Strain Rate Response of a Polycarbonate Under Uniaxial Compression," Session-Impact Behavior of Engineering Materials, Proceedings of SEM Annual Conference on Experimental Mechanics, Charlotte, North Carolina, June 2–4, 2003.
[2] T. Bjerke, et al., *Int. J. Plasticity* **18**, 549–567 (2002).
[3] P. Zoller, *J. Poly. Sci.: Part B: Polymer Phys. Eds.* **20**, 1453–1464 (1982).
[4] S.Z. Cheng and B. Wunderlich, *J. Poly. Sci.: Part B: Polymer Phys. Eds.* **24**, 1755–1765 (1986).

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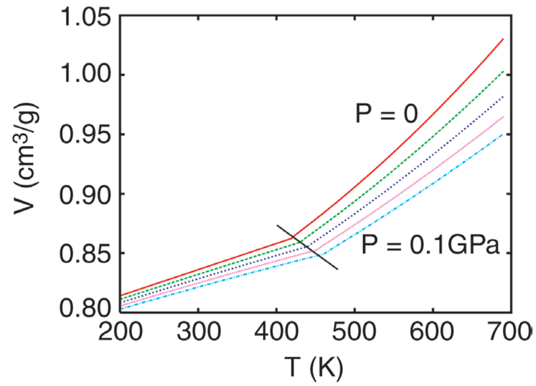

Fig. 1.
Specific volume for PC [3]. The solid line is the glass transition boundary. Pressures correspond to 0.0, 0.2, 0.4, 0.6, and 0.8 GPa.

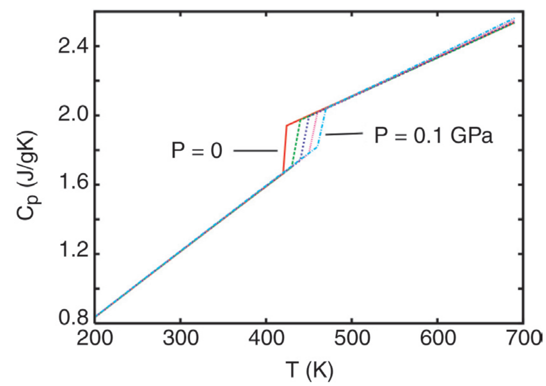

Fig. 2.
Constant pressure heat capacity for PC.

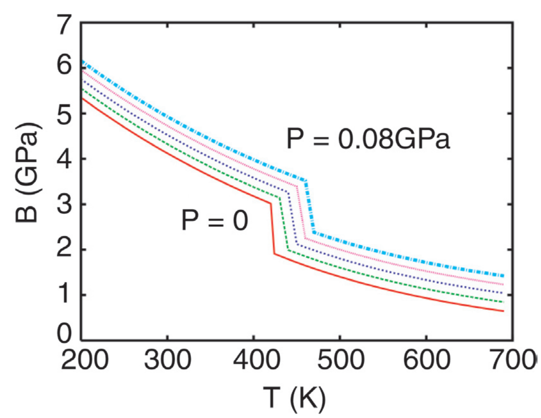

Fig. 3.
Isothermal bulk modulus for PC.

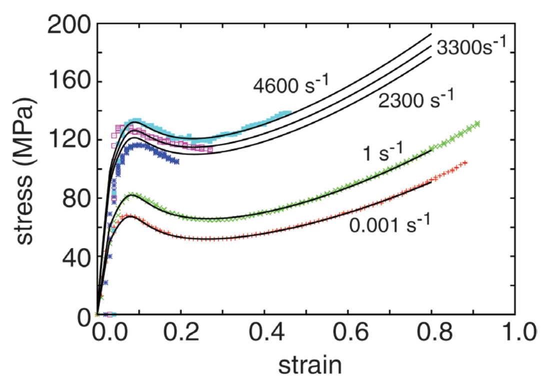

Fig. 4.
Experimental [1] and theoretical stress-strain behavior for PC.