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An experimental study on uniaxial ratcheting of polycarbonate polymers with different molecular weights

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ABSTRACT

The uniaxial ratcheting was experimentally observed on the polycarbonate (PC) polymers with different molecular weights (i.e., PC-7030PJ and PC-7020PJ) at room temperature. The effects of mean stress, stress amplitude, stress rate and peak hold-time on the ratcheting were observed. The results show that obvious ratcheting deformation occurs in the two prescribed polycarbonate polymers subjected to the stress-controlled cyclic loading; and the ratcheting strain accumulates cyclically in the direction of non-zero mean stress. The ratcheting greatly depends on the mean stress and stress amplitude, and the ratcheting strain increases more rapidly as the mean stress and stress amplitude increase. The ratcheting of two prescribed polycarbonate polymers is also significantly time-dependent, the ratcheting strains observed in the load cases with longer peak hold-time and at lower stress rate are larger than that with shorter peak hold-time and at higher stress rate. More importantly, a comparison of the ratcheting of two prescribed polycarbonate polymers shows that, at room temperature, the ratcheting of the polycarbonate polymer with a larger molecular weight (i.e., PC-7030PJ) is more remarkable than that with a smaller one (i.e., PC-7020PJ).

1. Introduction

Polycarbonate (PC) polymers have been widely used as a kind of structural materials due to its toughness, high heat distortion temperature, and excellent mechanical properties [1,2]. The structure components made by the PC polymers are often subjected to a cyclic loading, and fatigue failure is a main failure mode of such components. To better assess the safety and estimate the fatigue life of the structural components made by the PC polymers, it is important to observe and model the cyclic deformation of PC polymers.

Ratcheting, a cyclic accumulation of inelastic deformation will occur in the materials subjected to a stress-controlled cyclic loading with non-zero mean stress. In the last decades, a large number of experiments and constitutive models were performed and developed for the ratcheting of many metal materials at different temperatures: Wen et al. [3] investigated the uniaxial ratcheting behavior of Zircaloy-4 tubes at room temperature; Chen et al. [4] performed an experimental observation on the multiaxial ratcheting of eutectic tin–lead solder at room temperature; Gao et al. [5] experimentally observed the uniaxial ratcheting of SS304 stainless steel at elevated temperatures and then proposed a constitutive model to describe the temperature-dependent ratcheting of the steel; Kang et al. [6] also investigated the plastic flow properties of SS304 stainless steel during the uniaxial ratcheting tests at elevated temperatures; Furthermore, Kang et al. [7] performed an experimental observation on the multiaxial ratcheting of SS304 stainless steel at elevated temperatures and then developed a new multiaxial constitutive model by including a new definition of non-proportionality; Kang et al. [8] also investigated the time-dependent ratcheting of SS304 stainless steel presented in the cyclic loading at different stress rates and with or without peak stress hold; Kulkarni et al. [9] analyzed experimentally and theoretically the uniaxial and biaxial ratcheting in some piping materials; Mayama et al. [10] discussed the effect of memorization of back stress on the simulation of biaxial ratcheting of type 304 stainless steel; More recently, Xiong et al. [11] performed a detailed observation on the uniaxial cyclic deformation of extruded ZK60 magnesium alloy at room temperature, and Dong et al. [12] conducted a microscopic observation on the dislocation multiplication and movement during the ratcheting deformation of 20 carbon steel and made an attempt in investigate the micro-mechanism of ratcheting behavior.

Recently, much effort has been done in the studies on the ratcheting deformation of polymeric materials. Xu et al. [13] studied the uniaxial time-dependent ratcheting behavior of bronze powder filled polytetrafluoroethylene (PTFE) polymer at room and high

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temperatures, and the effects of peak stress hold-time, mean stress, stress rate, and pretension on the ratcheting were discussed. Li et al. [14] studied the uniaxial ratcheting of cerium oxide filled vulcanized natural rubber. Shariati et al. [15] experimentally investigated the uniaxial ratcheting and fatigue failure of polyacetal polymer. Yu et al. [16,17] observed the uniaxial and multiaxial ratcheting behaviors of vulcanized natural rubber. Pan et al. [18] demonstrated that the ratcheting deformation of polyetherimide polymer would occur both before and after the apparent yield, which is different from that of metal materials discussed in [3,5,8,11,12]. Jiang et al. [19] further revealed that the cyclic deformation of polymer materials consisted of two parts, i.e., the viscous recovery and accumulated unrecoverable deformations. The existing results show that the ratcheting of polymer materials is complicated and dependent on the different types of polymer materials. On the other hand, the effect of the molecular weight (a key physical parameter of polymer materials) on the ratcheting of polymer materials has not been addressed in the referable literature. In order to investigate the ratcheting of polymer materials more thoroughly, a large number of experimental researches are necessary still, especially for the polymer materials with different molecular weights.

Therefore, in this work, the uniaxial cyclic tests are performed to investigate the ratcheting of polycarbonate polymers with different molecular weights (i.e., PC-7030PJ and PC-7020PJ) at room temperature. The effects of mean stress, stress amplitude, peak hold-time and stress rate on the ratcheting deformation are discussed. More importantly, it is concluded that the ratcheting of the PC polymer with a larger molecular weight (i.e., PC-7030PJ) is more remarkable than that with a smaller one (i.e., PC-7020PJ).

2. Experiment procedures

Two kinds of polycarbonate polymers with different molecular weights, i.e., PC-7030PJ and PC-7020PJ, made by the Mitsubishi Engineering Plastic Company (Tokyo, Japan) were used as the test materials. Physical properties of PC-7020PJ and PC-7030PJ are listed in Table 1. Here, M_w is the weight-average molecular weight, M_n is the number-average molecular weight, and M_z is the z-average molecular weight, M_w/M_n stands for the molecular weight distribution of the polymers.

The plate specimens with 10 mm (width) × 80 mm (length) × 4 mm (thickness) were tested by MTS858-5KN. The axial strain was measured by an extensometer. All the tests were conducted at room temperature. In this work, three kinds of load conditions were used, i.e., uniaxial tension, creep and ratcheting tests, and the detailed load cases are listed in Table 2.

In this paper, to illustrate the ratcheting behavior more clearly, similar to that used in [3,5,8,11], the axial ratcheting strain ε_r is defined as:

$$\varepsilon_r = \frac{\varepsilon_{max} + \varepsilon_{min}}{2} \tag{1}$$

where ε_{max} is the maximum engineering strain in each cycle, and ε_{min} is the minimum one. Ratcheting strain-rate is defined as the increment of ratcheting strain ε_r in each cycle.

Table 1
Physical properties of PC-7020PJ and PC-7030PJ.

Material	$M_w/10^3$	$M_n/10^3$	$M_z/10^3$	M_w/M_n
PC-7030PJ	56.1	29.9	84.6	1.883
PC-7020PJ	38.9	21.0	58.7	1.858

Table 2
Loading conditions of uniaxial ratcheting tests.

Material	Mean stress (MPa)	Stress amplitude (MPa)	Peak hold time (s)	Stress rate (MPa/s)	Strain rate (s^{-1})
7020PJ/7030PJ	–	–	–	–	0.005
	–	–	–	–	0.0005
	50	0	3600	1	–
	20	10	0	1	–
	30	10	0	1	–
	40	10	0	1	–
	30	15	0	1	–
	30	20	0	1	–
	30	10	10	1	–
	30	10	60	1	–
	40	10	0	5	–

3. Results and discussion

3.1. Uniaxial tension and creep tests

From the stress–strain curves of the PC-7030PJ and PC-7020PJ polymers obtained in the uniaxial tensile tests at different strain rates and shown in Fig. 1, it is seen that, unlike the metals [3,5,8,11,12], the polycarbonate polymers present a nonlinear hardening before the yield strength is reached and an apparent softening phenomenon occurs after the yield strength point. Here, the yield strength point was defined as the highest point in the obtained tensile stress–strain curves of the PC-7020PJ and PC-7030PJ polymers. In addition, it is concluded from Fig. 1 that the tensile deformation of the PC-7020PJ and PC-7030PJ polymers is rate-dependent, and their stress–strain responses at 0.005 mm/s are higher than that at 0.0005 mm/s. More importantly, the yield strength of the PC-7020PJ polymer is larger than that of the PC-7030PJ polymer at room temperature.

Some basic mechanical properties of the PC-7020PJ and PC-7030PJ polymers obtained from the stress–strain curves shown in Fig. 1 are listed in Table 3.

To demonstrate the viscosity of the PC-7020PJ and PC-7030PJ polymers, the creep tests are performed and the obtained creep curves are shown in Fig. 2. It is seen that: (1) The PC polymers show apparent viscosity, even at room temperature. (2) A necking occurs in the PC-7030PJ polymer during the holding at 50 MPa, and about 80% strain of the PC-7020PJ polymer is recovered once the specimen is unloaded to zero stress. That is to say, the creep resistance of the PC polymer with lower molecular weight is far superior to that with larger molecular weight.

3.2. Ratcheting tests

3.2.1. Effects of stress levels

From the experimental results obtained in the stress-controlled cyclic tests with constant stress amplitude and various mean stresses and shown in Fig. 3, it is seen that: (1) apparent ratcheting occurs during the cyclic tests of both the PC-7030PJ and PC-7020PJ polymers. The ratcheting strain increases with the number of cycles in the direction of tensile mean stress, while the ratcheting strain rate decreases rapidly in the first beginning of cyclic loading and a stable ratcheting with a constant ratcheting strain rate is reached after certain cycles, which is similar to that observed in the cyclic tests of other polymer materials [13–18]. (2) Mean stress has significant influence on the uniaxial ratcheting of the PC-7030PJ and PC-7020PJ polymers, and the ratcheting strains increase with the increase of mean stress. It is also similar to that observed for other polymers [18]. (3) Comparing the ratcheting behaviors of the PC-7030PJ and PC-7020PJ polymers with