International Journal of Impact Engineering 86 (2015) 265–273

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Predicting the low-velocity impact behavior of polycarbonate: Influence of thermal history during injection molding

Yingjie Xu *, Huan Lu, Tenglong Gao, Weihong Zhang

Engineering Simulation and Aerospace Computing (ESAC), Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China

A R T I C L E I N F O

Article history:
Received 30 April 2015
Received in revised form
14 July 2015
Accepted 20 August 2015
Available online 28 August 2015

Keywords:
Polycarbonate
Yield stress
Injection molding
Izod impact
Finite element simulation

A B S T R A C T

The influence of the thermal history experienced during injection molding on the low-velocity impact behavior of polycarbonate (PC) is investigated. An integrated methodology consisting of prediction of the processing-induced yield stress and finite element simulation of the impact behavior is proposed. The yield stress is first evaluated directly from the temperature history experienced during injection molding process. A strain rate-dependent elastic-plastic model with the modification to combine the influence of processing thermal history is developed to model the mechanical behavior of PC. Finite element simulation for notched Izod impact test is then conducted to analyze the impact behaviors of PC specimens with different thermal histories. Numerical results of the fracture energies are compared with experimental measurement to verify the proposed methodology. In addition, a series of numerical simulations are performed to examine the influence of thermal history experienced during injection molding on the plastic deformation and fracture energy of PC specimens.

1. Introduction

Polycarbonate (PC) is a thermoplastic polymeric material with transparent nature, high ductility, impact resistance and comparatively light weight. Indeed, the impact resistance of PC, as measured from Izod impact tests [1,2], is among the highest for thermoplastics [3], making it suitable for impact applications including aircraft canopies, face shields, goggles, windshields and windows and blast shields. Impact response of the PC structures is thus a subject of critical interest.

The impact response of PC has been extensively studied in the literature by experimental research works, ranging from high velocity impacts [4–9] by means of gas gun impact tests to low velocity impacts [1,2,10,11], and by means of falling weight tests or Izod impact tests. Shah [4,5] carried out low velocity single and multiple impact tests on a thin PC armor plate. The impacts were conducted on a horizontal and diagonal path to explore the plate vulnerability against the in-coming single and multiple projectiles striking at various locations. Gunnarson et al. [6] performed impact tests on PC plates of various thicknesses. The time histories of the maximum deflection of 3.0, 4.45 and 5.85 mm thick plates for impact velocities between 10 and 50 m/s were obtained. It was also observed that the penetration velocity for the 5.85 and 3.0 mm thick plates equaled 80 m/s and 65 m/s, respectively. Mckenzie et al. [7] performed a series of impact tests with various impact velocities (10–50 m/s) on circular PC plates with thicknesses between 3 mm and 12 mm. They identified a number of failure mechanisms in the plates and constructed a fracture map which incorporates the effect of plate thickness and impact velocity. Wright et al. [8] conducted high velocity ballistic tests on PC plates with thicknesses of 2, 5 and 12 mm. Mechanisms of deformation and subsequent fracture of the plate were identified by the experimental observations. Inclined impact on thin PC plates (the thickness is less than 6.4 mm) was also investigated by Li and Goldsmith [9], who noticed that the resulting perforation hole exhibits a much smaller diameter than the projectile, indicating a substantial capability for recovery. Fraser et al. [1] studied the impact fracture behavior of PC Izod specimens with a range of notch tip radius. Experimental results indicated that blunt notches gave constant fracture toughness values. However, for intermediate notch tip radius the fracture was much more complex. In addition, comparison of results for two molecular weight grades indicated that the behavior was molecular weight-dependent. Cheng et al. [10] tested standard PC Izod specimens of two thicknesses: 3.18 mm and 6.35 mm. It was found that the transition from brittle to ductile failure occurred between those two thicknesses. Experimental results showed that the averaged

---

* Corresponding author. Northwestern Polytechnical University, P.O. Box 552, Xi'An, Shaanxi 710072, China. Tel.: +86 29 88493914; Fax: +86 29 88495774.
E-mail address: xu.yingjie@nwpu.edu.cn (Y. Xu).

http://dx.doi.org/10.1016/j.ijimpeng.2015.08.013

impact fracture energies of the wider and thinner specimens were 112 J/m and 918 J/m, respectively. Lombardo et al. [11] studied 3.18 mm thick samples with sharp and standard notch. The sample with sharp notch had 80 J/m fracture energy. The impact fracture energy of sample with standard notch was found to be 1000 J/m. Moreover, over several decades, the group at Cavendish Laboratory at University of Cambridge [12] has made important contributions to experimental analysis and mechanisms study of PC and other polymers under solid particle impact.

A numerical model that correctly simulates the impact behavior can provide convenient and useful guidelines on product design and effectively decrease the experimental cost. A number of numerical studies based on the finite element method have been performed to compute the dynamic response of PC under impact loading. Dorogoy et al. [13,14] conducted systematic studies on the inclined ballistic impact in thick PC plates by modeling and experimentation. In the work of Dorogoy et al. [13], a thick PC plate impacted by an armor piercing 7.62 mm projectile was investigated experimentally and numerically. A 3D transient non-linear adiabatic finite element simulation was performed using ABAQUS. Two combined failure criteria: Ductile failure with damage evolution and tensile failure were used. The properties of PC were described by a strain rate and temperature dependent model. In this investigation, the trajectories, penetration velocities, depths of penetration, and the damage zone around the trajectories of the projectile were fully characterized. The penetration process in unconfined and confined thick PC plates was also investigated experimentally and numerically [14]. The numerical results indicated that the confinement introduced a negative triaxiality within the confined plates prior to impact. The shallower penetration in confined targets was due to the higher negative triaxiality which reduced the ductile damage during penetration, while the hydrostatic pressure reduced the brittle fracture mechanism. Shah [5] simulated the plastic deformation of a thin rectangular PC plate under low velocity impact. LSDYNA was used to simulate the impact event for the plate midpoint, the horizontal edge, and the diagonal edge. A metal plasticity model was used for the target plate. A surface to surface friction-less contact was defined between the projectile and the target plate. Bobaru et al. [15] presented experimental and computational results for the impact of a spherical projectile on a thin glass plate with a thin PC backing plate. The peridynamic constitutive model for a brittle material was applied for modeling the PC and glass plates. The evolution of damage and its connection to the stress waves' propagation in the PC and glass plates was described in detail. The simplified boundary conditions used in the computational model was found to be the most important factor for the differences between the experiments and the computations in this problem. The evolution of stress and strain fields in PC specimens during the Izod impact test was analyzed numerically in Ref. 16. The computations were full 3D transient analyses using explicit time integration and accounting for finite strains. The numerical results showed the clear differences between the stress and strain fields that develop in the Izod specimens with various thicknesses.

Injection molding is the most widely used process for manufacturing polymer products [17,18]. In this process, the melted polymer is injected into a mold cavity with a desired shape and then cooled down under a high packing pressure. It has been known that the mechanical properties of an injection molded polymer are influenced by its thermal history during the processing stage [19–22]. In the work of Govaert et al. [19,20], it was proved that the thermal history experienced upon solidification from the melt has an influence on the yield stress of molded PC products. Thus, for a PC product under impact loading, we can conclude that the differences in thermal history during injection molding have inevitable consequences for its impact behavior. However, few experimental or modeling studies have been carried out for investigating the influence of thermal history on the impact behavior of PC.

In the present study, we aim to develop an integrated methodology which combines the evaluation of the yield stress of PC after processing and the finite element computation of the impact behavior of PC in a low velocity Izod impact test. The evaluation of the yield stress from thermal history during injection molding is based on the method developed by Govaert et al. [19–21]. The notched Izod impact tests are carried out to analyze the impact behaviors of PC specimens with different thermal histories. A finite element simulation for the notched Izod impact test is then performed using a strain rate-dependent elastic-plastic model of PC with the modification to combine the influence of processing thermal history. A series of numerical simulations are performed to examine the detailed influence of thermal history on the resulting impact behavior of PC. The numerical results are compared to the test results of PC specimens with different processing conditions to illustrate and assess the predictive capability of the proposed methodology.

2. Predicting the yield stress of PC from processing thermal history

2.1. Predictive model of the processing-induced yield stress of PC

In this study, the prediction of yield stress of PC from processing thermal history is based on a phenomenological approach developed by Govaert et al. [19–21]. They assumed the physical processes of the evolution of yield stress during processing are identical to those governing the evolution of yield stress during annealing. Thus, the evolution of yield stress of PC during annealing process is firstly investigated in this paper. The tensile samples of PC Lexan 141R with two different mold temperatures (90 and 140 °C) are injection molded in School of Science, Northwestern Polytechnical University, PR China. Horizontal injection molding machine LIGUANG FL-220MO is used to fabricate test specimens. The geometry of molded dog-bone specimen is shown in Fig. 1.

The glass transition temperature (T_g) of PC determined by the Dynamic Mechanical Thermal Analysis (DMTA) is 148 °C. At high temperatures especially for the range near T_g, the increase in yield stress is more pronounced, as observed by Golden et al. [23], and Bauwens-Crowet and Bauwens [24]. Thus in this study all the samples are annealed for a specified period of time at four different annealing temperatures (80, 100, 120 and 130 °C). After the required annealing period, samples are slowly cooled to room temperature. Tensile tests are then performed under a constant strain rate of $10^{-2}\,\mathrm{s}^{-1}$ to determine the yield stress for all the samples. All experiments are conducted in electro mechanical universal testing machine 310R-5KN from TESTRESOURCES.

Fig. 2 shows the evolution of yield stress of samples obtained by 90 °C mold temperature for four different annealing temperatures. It is observed that the yield stress is increased with annealing time and the increase is more pronounced for higher temperatures, which coincides well with the observations in Refs. 22–24. The experimental results of the yield stress under various annealing temperatures can be combined into a single master curve for a reference temperature by using annealing time–temperature superposition [19]. In Fig. 3, the master curves for the yield stress of samples with 90 and 140 °C mold temperatures are both presented for a reference annealing temperature of 23 °C (room temperature). The shift factor $a_T\,(T)$ to construct the master curve can be described by an Arrhenius relation: