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Test Method

Tensile fracture behavior of a biodegradable polymer, poly(lactic acid)

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Abstract

The stable and dynamic fracture behavior of a biodegradable polymer, poly(lactic acid) (PLA), was investigated using single-edge-cracked tensile specimens. To study the dynamic effect of brittle facture, the specimens were pin-loaded using a special jig that allowed them to split and fly off in the loaded direction after fracture. The non-elastic effect of viscoelastic and plastic deformations was also measured using an optical high-speed extensometer, which consisted of an optical fiber and a position-sensing detector (PSD). For the stable and dynamic fracture process, external work applied to the specimen and its fracture surface was partitioned into U_s and U_d, and A_s and A_d, respectively. The energy release rate, G_s, for stable crack growth was determined using U_s/A_s. The kinetic and non-elastic energies were measured and subtracted from U_d to evaluate the fracture energy for the dynamic process, E_f. The dynamic energy release rate, G_f, was then determined as E_f/A_d. G_d was also obtained as U_d/A_d to correlate with G_s and G_f, and the results are discussed.

Keywords: Material testing; Biodegradable polymer; PLA; Fracture; Crack growth; Elastic energy

1. Introduction

Biodegradable polymers have recently been introduced to various fields as alternatives to traditional materials. For example, poly(lactic acid) (PLA) is attracting attention as a medical biomaterial owing to its biocompatibility and absorbability in human bodies [1]. In orthopedic and oral surgeries, PLA is often used for bone fixation devices at fracture sites. PLA devices have an important advantage over traditional metal devices; there is no need for a second operation to remove the devices after recovery, relieving the physical and mental burdens on patients [2,3]. However, there is a problem; PLA devices can crack during treatment since they are not as resilient as metal devices. Therefore, it is necessary to develop more reliable PLA devices in terms of their mechanical properties, such as their strength and fracture toughness. In addition, the precise evaluation of their mechanical properties is required to assure the safety of PLA devices. Conventionally, PLA specimens with flat, smooth surfaces have been subject to tensile and bending tests. However, PLA devices in the human body can develop flaws and surface defects during the degradation process. Therefore, it is important to examine the fracture behavior using

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PLA specimens that are notched or cracked. To date, only a few experimental studies examining the fracture behavior of PLA have been published.

To study this problem, we fabricated PLA plates from pellets using a hot press, and measured the fracture behavior of single-edge-notch-bend specimens under static and impact loading [4–7]. As a fracture parameter that controls crack growth, the stress intensity factor K or the J-integral was determined using a load–displacement diagram, i.e. the external work applied to the specimen. Essentially, PLA undergoes brittle fracture, and K and J depend on the loading rate. The concept of K or the J-integral plays an important role in understanding fracture behavior. However, more detailed investigation of the effects of inertia or the kinetic energy of the specimen during dynamic crack propagation is required [8–21]. It has also been suggested that the non-elastic effect of the viscoelastic and plastic deformations of the specimen should be determined and considered in the fracture analysis [20].

This study examined these two effects in PLA specimens. To examine the kinetic effect, single-edge-cracked tensile specimens were pin-loaded using a special jig, so that they could split and fly off after fracture. The non-elastic effect of viscoelastic and plastic deformation was also measured using an optical high-speed extensometer [22]. The tensile specimens exhibited stable crack growth in the early stage of fracture and dynamic crack propagation in the later stage. Therefore, fracture was divided into two processes: the external work applied to the specimen and the corresponding fracture surface was partitioned into U_s and U_d, and A_s and A_d, for the stable and dynamic processes, respectively. The energy release rate for stable crack growth, G_s, was then determined as U_s/A_s. The energy release rate for dynamic crack propagation, G_f, was evaluated by first quantifying the kinetic and non-elastic energies. Then, these energies were subtracted from the external work, U_d, to give the fracture energy, E_f. Finally, G_f was determined as E_f/A_d. The values of G_d ($= U_d/A_d$) were also obtained for comparison with G_s and G_f.

2. Specimen material and experimental methods

PLA pellets (Lacty#9030; Shimadzu) were used as specimen material. The average molecular weight was about 2×10^5, and the glass transition and melting temperatures were 61 and 175 °C, respectively. Three-mm-thick PLA plates were fabricated using a hot press with an attached water-cooling system. The pellets were melted at 180 °C, pressed under 30 MPa for 1 h, and then quenched with iced water for 10 min to prevent crystallization of the material.

Experiments were performed on single-edge-cracked tensile specimens, as shown in Fig. 1. The specimens measured 190 mm in length and 20 mm in width. To change the fracture initiation load of the specimens, sharp pre-cracks with lengths between 2 and 5 mm were generated by tapping a fresh razor blade into a pre-machined saw cut on the specimen edge. As illustrated in the figure, the specimen was clamped rigidly at its lower part and loaded on the upper part using a steel pin and grip.

A load was introduced using a special jig consisting of four steel bars, as shown in Fig. 2. The shape of the jig allowed the specimen to split and fly off in the load direction after fracture. The height the specimen attained was recorded with a thin paper pipe (0.3 g) inserted between the bars, which stopped at the highest position reached by the upper part of the split specimen (30 g). This was used to estimate the elastic energy in the specimen. In this study, the elastic energy in the jig was disregarded since it was much stiffer than the specimen. All the specimens were tested under displacement-controlled conditions using a tensile-testing machine. Tests were performed at room temperature and at a constant crosshead rate of 1 mm/min.

Fig. 1 also shows the configuration used for the displacement measurements of the loading point and the region underneath the pre-cracked position, i.e. the center of the specimen. The loading-point displacement was determined with the tensile-testing

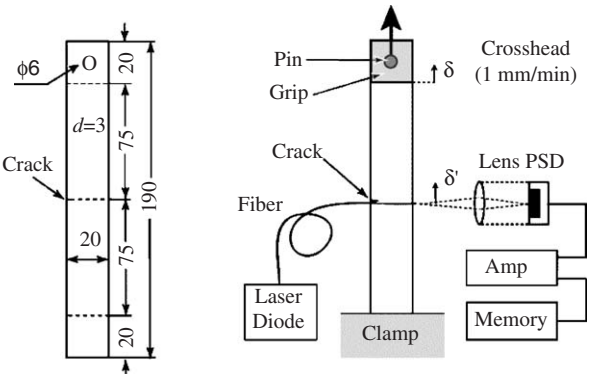

Fig. 1. Specimen geometry and the experimental setup used for loading and displacement measurement using an optical fiber and position-sensing detector (PSD).