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Test Method

Deformation to fracture evolution of a flexible polymer under split Hopkinson pressure bar loading

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ABSTRACT

The deformation-to-fracture evolution of a flexible polymer material under high-strain-rate compressive loading conducted by a split Hopkinson pressure bar (SHPB) setup was investigated. Representative tests were carried out at different strain rate levels, followed by the characterization of dynamic damage after each test. Craze and crack patterns on the end surface of the specimen were carefully analyzed. The failure patterns appear along the radial and circumferential directions. The sequence of their formation with increasing strain/stress level was revealed. The mechanisms resulting in the craze and crack patterns were analyzed. The heterogeneous stress distribution in the specimen and the resultant damage morphologies were demonstrated. This research not only shows the deformation-to-fracture evolution of a flexible polymer material under SHPB loading, but also provides a better clarification of the localized stress distribution in the tested material via SHPB technique.

1. Introduction

The split Hopkinson pressure bar (SHPB) is a mature method and a commonly used apparatus to accurately test the dynamic compression properties of various materials at strain rates ranging from 100/s to 10000/s [1–11]. Especially for a flexible polymer, the extremely low wave impedance and considerable deformation strain result in the challenge for dynamic testing technique [1,4,12–14]. Besides, the impact process during a SHPB test occurs in less than a few milliseconds. This short time frame leads to the difficulty of characterizing the microscopic deformation morphologies and the material damage mechanisms occurring during high-rate loading.

In some reports [8–11], a high-speed digital camera was employed to record the dynamic deformation and fracture process of materials during the SHPB test. The recorded images can reveal the overall deformation and macroscopic crack initiation and propagation. In a previous study on a flexible polymer, the authors used the high speed recordings to calculate the ratio of lateral to axial deformation with dynamic straining [11]. Based on the ratio-straining data, the evolution of microscopic damage behavior during the dynamic compressive loading was indicated. However, direct characterization of microscopic dynamic deformation and fracture behavior is still impossible and studies of the corresponding damage mechanisms with straining are not known.

Characterizing deformation and fracture behavior of the material itself during dynamic loading, and not only the overall specimen response, is needed to reveal the dynamic damage mechanisms with straining [11,15,16]. It is important to explore the physical origin of impact-resistant performance of a material [6]. Furthermore, to interpret the experimental results, the dynamic compressive response of a material in the SHPB test [8], as well as the spatial and temporal stress distributions in the material subjected to SHPB loading have to be known and understood [5,8].

In this paper, a polyurethane elastomeric polymer material [11,17], which is a soft, flexible and amorphous polymer, was investigated in SHPB experiments. A specially designed experimental procedure was conducted to characterize in detail the microscopic damage behavior. The deformation-to-fracture evolution and the corresponding morphologies of crazes and cracks were revealed by a post-test observation after each SHPB experiment. The study presented in the current paper is not only for characterizing the deformation-to-fracture evolution process of a polymer material in the SHPB test, but also for clarifying the localized stress distributions in the loaded material by the SHPB setup, as well as for revealing the consequences for the interpretation of the test results on a flexible polymer material.

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2. Experimental procedure

A polyurethane elastomeric polymer material was prepared by mixing two parts of the water white clear urethane liquid pre-polymers [11,17]. It is a transparent, flexible and UV resistant polymer with an amorphous microstructure. It shows a high strength increase under dynamic loading with a good ductility and the resultant strain energy absorption capability [11]. The dynamic experiments were conducted using a SHPB apparatus developed at TU Delft, which can generate a maximum sample rate of $2.5*10^6$ samples/s and a loading pulse duration of 155 μs. The material of the striker bar, input bar and output bar is Aluminium alloy with Young's modulus $E = 71.7$ GPa, density $\rho = 2700\ kg/m^3$, and Poisson ratio $\nu = 0.33$. The dimensions of these 3 bars are respectively 400 mm, 2000 mm and 2000 mm in length and all are 20 mm in diameter. The tested specimen of the polymer material is a circular cylinder with 10 mm diameter and 5 mm length, which is positioned in between the input bar and output bar. The ends of these 3 bars are carefully polished and the lubricant of grease is used for minimizing the friction during dynamic loading. The SHPB apparatus was carefully evaluated and proved to be a reliable dynamic test setup for soft polymer materials. More information can be seen in Ref. [11].

High-rate loading was conducted to induce final fragmentation, which produced a complete stress-strain relation at a strain rate of 5700/s (see Fig. 1). For proper evaluation of the testing results of the SHPB, a careful check on the dynamic experimental procedures has been carried out and the issues of stress equilibrium and constant strain rate loading have been confirmed, which are illustrated in Ref. [11]. Meanwhile, a high-speed camera was used to synchronously record the dynamic deformation process until final fragmentation takes place. The homogeneous dynamic compressive deformation until failure can be confirmed, which indicates stress equilibrium after stress wave propagates into the specimen at the beginning of dynamic compression. The ratio of lateral deformation to axial deformation with straining until failure was approximately determined, based on the recorded high-speed camera images. The stress-strain curve was divided into four stages according to the different damage mechanisms. From initial deformation to final fragmentation, no damage is observed at stage I (before 86 MPa stress-5.5% strain); crazing is seen at stage II (before 166 MPa stress-45% strain); micro cracking is found at stage III (before 446 MPa stress-67% strain); and fragmentation is viewed at stage IV (before 782 MPa stress-78% strain), respectively. All these results are reported in Ref. [11].

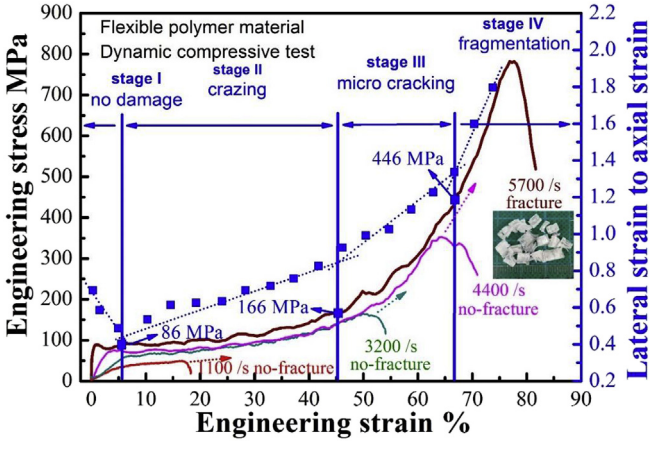

Fig. 1. Engineering stress-strain curve of the flexible polymer material tested at a strain rate of 5700/s, with the deformation-to-fracture evolution process approximately determined by the ratio of lateral deformation to axial deformation recorded by a high-speed camera [11], as well as the engineering stress-strain curves at lower strain rates for revealing the microscopic deformation and fracture morphologies and investigating the corresponding damage mechanisms at different stress-strain stages from I to IV.

In order to directly characterize the microscopic morphologies and to reveal the corresponding damage mechanisms at different stages, lower-rate loadings on the polymer specimens were conducted which produced the deformation or/and fracture behavior up to the corresponding stress-strain stages of I to IV. At these lower strain rates, fracture of a specimen was not induced by the first pulse loading in each test. Thus, the specimens experienced multiple pulse loadings before cracking is initiated. An absorption bar was added to the SHPB setup, which is initially in contact with the transmitter bar and traps the transmitted pulse for minimizing/reducing the effects of multiple pulse loadings on the deformed specimen. The strain rates were also carefully selected for attaining the deformed specimens for the post-test observations for characterizing the dynamic damage at the corresponding stress-strain stages.

For motivating the sequentially observed increase of damage in the individual dynamic test at a strain rate of 5700/s, a series of dynamic tests at increasing loading rates are conducted for coupling to the strain/strain energy density level with the different stress-strain stages in Fig. 1. The selected strain rates are 1100/s for stage II, 3200/s for stage III, and 4400/s for stage IV, respectively (see Fig. 1). Herein, it is noted that during dynamic straining, the deformed specimens always stay in between the input bar and output bar of the setup. After each dynamic compressive test at the corresponding strain rate, the optical microscopy (OM) and scanning electron microscopy (SEM) were employed to carefully analyze the deformed specimen. Both end sides were analyzed in order to confirm the uniform deformation of the specimen and to construct the 3D damage morphology under dynamic loading.

3. Experimental results and discussions

Before a SHPB test, the end surfaces of the polymer specimens were checked, which are smooth and featureless without any initial damage (see Fig. 2(a)). In order to indicate and discuss the damage development, the radial and circumferential directions are considered, as marked by red and blue arrows, respectively.

After the dynamic compressive test at a strain rate of 1100/s calculated from the first loading pulse, the end surface of the deformed specimen emerges some radial crazes, radiating from the center of the end surface (see Fig. 2(b)). These radial crazes are distributed homogeneously surrounding the center zone due to an initially uniform deformation and the amorphous nature of the polymer material. The locally enlarged image confirms the formation of crazes without growing into cracks, as shown in Fig. 2(c). In a partial region, crazes were also formed in the circumferential direction. The interaction of radical crazes and circumferential crazes is shown in Fig. 2(d). These observations indicate that after the radial crazes emerge in the full circle region, the circumferential crazes are formed, which only occur in a quarter circle region in the current case. Thus, we can conclude that under a SHPB loading, crazes are firstly formed in radial direction, then in circumferential direction, and their interactions are also induced. These correspond to the microscopic morphologies of crazing at stage II in Fig. 1.

After the dynamic compressive loading at a strain rate of 3200/s calculated from the first loading pulse, the end surface of the deformed specimen is full of the numerous crazes along both the radial and circumferential directions (see Fig. 3(a)). The locally enlarged image reveals the interaction of the radial crazes and circumferential crazes, which makes the end surface very rough (see Fig. 3(b)). Furthermore, micro cracks were also found in the circumferential direction, which were formed from the growth of circumferential crazes [11,17–21]. Therefore, under a SHPB loading, micro cracks are formed in the circumferential direction. It corresponds to the microscopic morphology of micro cracking at stage III in Fig. 1.

After the dynamic compressive loading at a strain rate of 4400/s calculated from the first loading pulse, the end surface of the deformed