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Compressive response of a glass–polymer system at various strain rates

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ABSTRACT

A glass–polymer system of a polyurethane elastomeric matrix with a single 3 mm-diameter glass particle was investigated using a split Hopkinson pressure bar (SHPB) setup for revealing the dynamic compressive mechanical response. This study produced the characteristics of the dynamic stress–strain relation and the relations for the rate dependencies of yield stress, maximum stress and strain energy. A high-speed camera was applied to record crack initiation, propagation and fragmentation fracture. Scanning electron microscopy (SEM) was employed to explore the dynamic damage mechanisms. The static and dynamic compressive mechanical properties of a glass–polymer system were compared with these of monolithic polyurethane elastomeric polymer material. The results of this study provide the dynamic response at unit cell level and are used for development and evaluation of transparent, impact-resistant protection concepts of glass–polymer systems.

1. Introduction

In the last few decades, polymers and polymer structures have been extensively investigated to develop impact-resistant devices. An increasing number of applications relate to dynamic loading and high-strain-rate deformation (Huang et al., 2003; Ray and Okamoto, 2003; Singh et al., 2011; Bartczak et al., 1999; Deschanel et al., 2009; Gao et al., 2011; Wang et al., 2006; Smith and Chu, 1998; Song and Chen, 2004; Chen et al., 2002; Siviour et al., 2005; Meng et al., 2014; Sun et al., 2009; Mulliken and Boyce, 2006; Ochola et al., 2004). Recently, research of the Netherlands Organisation for Applied Scientific Research (TNO) on the impact resistance of transparent hybrid glass–polymer systems (layered and particle-matrix systems) showed the potential for protection applications. A soft, transparent polyurethane elastomeric polymer, Clear Flex 75 (CF 75 in short) was selected as matrix (van Ekeren and Carton, 2011; Fan et al., 2015c). Knowledge about the impact resistance of particle-polymer systems is also relevant for propellants (Drodge et al., 2010; Williamson et al., 2008), consisting of a polymer binder and solid energetic particles. Impact damage will change the combustion properties of the propellant and also their performance. Particle fillers play an important role in modifying these dynamic properties.

Based on this background, a programme combining experimental and computational research was defined, which focuses on the dynamic mechanical response of hybrid particle-polymer systems under high-rate loading. In this research programme, CF 75 polymer is the matrix material with embedded single and multiple particles. In the computational part, multi-scale modelling techniques for dynamic conditions have been developed (Karamnejad et al., 2013). In the experimental part, the split Hopkinson bar (SHB) technique has been applied to study the dynamic mechanical response of the monolithic CF 75 polymer material (Fan et al., 2015b, c), providing the

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input data at material level for the numerical modelling. Furthermore, the dynamic mechanical response at the level of a unit cell with a single particle (Benseddiq et al., 2006; Fan et al., 2015a) is important to be investigated.

The current paper presents the results of the experimental research on the dynamic compressive response at unit cell level. A special glass–polymer system is designed as the tested specimen, consisting of a matrix of CF 75 polymer material with an insert of a single glass particle. The split Hopkinson pressure bar (SHPB) (Fan et al., 2015c) is employed for the dynamic mechanical tests, which has been widely used to derive the stress–strain curve under dynamic loading for a variety of engineering materials (Gray, 2000; Chen and Song, 2011; Field et al., 2004). Accompanying the dynamic mechanical loading, a high-speed camera is employed to record the deformation and fracture behaviour of the specimen (Kajberg and Wikman, 2007; Gilat et al., 2009; Koerber et al., 2010; Chen et al., 2014). By testing the glass–polymer system in the SHPB setup, the dynamic mechanical properties and dynamic mechanical response at macro scale level can be derived. Various strain rates were applied to study the rate dependency of mechanical properties, such as yield stress, maximum stress and deformation capacity. Coupled with the high-speed camera recordings, a scanning electron microscopy (SEM) is used to observe crack initiation, propagation and fragmentation, as well as to analyse the damage mechanisms. The dynamic mechanical properties of the glass–polymer system were quantitatively analysed and compared with these of monolithic CF 75 polymer material.

2. Experimental procedure

2.1. Specimen preparation

The production procedure of CF 75 polymer material has been described in references van Ekeren and Carton (2011), Fan et al. (2015b,c). In the current research, for preparing the glass–polymer system specimen of CF 75 polymer matrix with a single 3 mm-diameter glass particle, a mixed liquid of Part A (a polyol) and Part B (an isocyanate) is injected into the mold to be half-full, and then 6 h is stopped followed by the placement of a 3 mm-diameter glass particle in the centre of the mold. Afterwards, the mixed liquid is poured into the mold again until it is completely full. Finally, the same curing procedure is processed with 16-h preservation at room temperature followed by 3-h post-curing at a temperature of 70 °C. The 3 mm-diameter glass particle has a significantly higher hardness than the CF 75 polymer matrix. The constitution of the mold should be specified, which determines the geometry and dimension of the specimen, as shown in Fig. 1. It consists of two pieces of flat plates. One plate has vertical holes with a dimension of 10 mm diameter and 5 mm depth, which ensures the same dimension and the parallel side surface of the prepared specimen.

The prepared specimen of a glass–polymer system has a cylindrical geometry with a dimension of 5 mm length and 10 mm diameter, and a single 3 mm-diameter glass particle placed in the centre of the CF 75 polymer matrix. This specifically designed specimen is prepared for quasi-static and dynamic compressive tests.

2.2. Quasi-static mechanical properties tests

Quasi-static compressive mechanical tests were carried out on the specimen of a glass–polymer system of CF 75 polymer matrix with a single 3 mm-diameter glass particle at room temperature, by using a computer-controlled, servohydraulic Instron-8810 testing machine at a strain rate of 0.01/s. Three specimens were tested to examine the repeatability of the experimental results.

Fig. 2 shows the corresponding engineering stress–strain plot of the glass–polymer system. In the same figure, the quasi-static compressive mechanical response of the monolithic CF 75 polymer material is given as a reference. The engineering stress-strain curve can be divided into three stages. In stage I, the curve displays a nonlinear stress–strain relation with a plateau-like region in which a small stress increase is coupled to a relatively large deformation (30% engineering strain). This behaviour is similar to that of monolithic CF 75 polymer material. However, an enlarged image shows that the stiffness of the glass–polymer system is slightly higher than that of monolithic CF 75 polymer material. The similarity in behaviour indicates that the deformation of the glass–polymer system in stage I is controlled by the polymer matrix. The increased stiffness is mainly caused by the embedded glass particle. Crack initiation may be induced at the glass–polymer interface, as schematically shown in Fig. 3(b), due to a lateral stress resulting from an axial compressive stress exerted on the specimen of the glass–polymer system (see Fig. 3(a)).

In stage II, at increasing stress, the engineering stress–strain curve obviously deviates from that of the monolithic CF 75 polymer material as pointed out by arrow '1' in Fig. 2, which was induced by the glass particle. Induced by axial deformation and crack opening from the glass–polymer interface, cracking inside the glass particle can be initiated due to the stress transferred through the polymer matrix. Beyond about 40% deformation, the load acts almost as a contact force for the glass particle. High amplitude stresses were transferred through a thin compressed polymer layer, as shown in Fig. 3(c). Herein, the lateral debonding process induced by crack opening from the glass–polymer interface occurs (Fan et al., 2009, 2015c; Bardella and Belleri, 2011). The crack propagation in the glass particle was induced by an increased axial load. Meanwhile, crack initiation could be induced in the polymer matrix.

With a further increase of axial deformation, fracture of the glass particle is caused at an increasing stress as pointed out by arrow '2' in the engineering stress–strain curve (see Fig. 2). Herein, the axial deformation can be determined as approximately 40% engineering strain, which agrees well with the dimensions of a 5 mm long specimen and a 3 mm diameter thick glass particle. Afterwards, the broken glass pieces fill the large void, as shown in Fig. 3(d). Then, the deformation of the glass–polymer system will again be dominated by the CF 75 polymer matrix. The engineering stress–strain curve maps back on the monolithic curve, which is defined as stage III in Fig. 2. The stress