Polymer Testing 53 (2016) 314–322

Contents lists available at ScienceDirect

Polymer Testing

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

Material properties

High strain rate out-of-plane compression properties of aramid fabric reinforced polyamide composite

Xiuyang Qian [a, b], Hongxin Wang [a, b], Dashi Zhang [a, b], Guilin Wen [a, b, *]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, PR China
[b] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, PR China

ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form
27 May 2016
Accepted 15 June 2016
Available online 20 June 2016

Keywords:
Single polymer composites
Hot compaction
Compression property
High strain rate
Polymer testing

ABSTRACT

The composite-structure protective systems in head-on collision with objects are largely subjected to dynamic compression load along the thickness of composite structure. A typical plain weave aramid fabric reinforced polyamide (PA) composite, which is defined as one of single polymer composites (SPCs), is addressed in this paper. Firstly, in the process of sample preparation, processing characteristics of the single polymer composites are skillfully achieved and discussed using differential scanning calorimetry (DSC) and capillary rheometer. Secondly, the out-of-plane compression properties of the composite are studied on Split Hopkinson Pressure Bar (SHPB) apparatus in the strain rate range of 400–1200s^{-1}. Effects of fiber content and strain rate on dynamic off-plane compression properties are investigated and quasi-static properties are obtained on a universal testing machine as a comparison. Results provide a basis for selecting composite composition and lay-up for designing armor with improved impact resistance. Additionally, penetration of the resin through the fabric is observed by the digital microscope and the internal damage of the laminates is qualitatively predicted by the microstructure of the internal fabric yarns.

1. Introduction

High performance polymer fibers have remarkable properties such as lightness, flexibility, high Young's modulus and good impact resistance, which make them attractive candidates in aerospace, robot equipment, automobile industries, and so on. Furthermore, subject to the heavy burdens of waste material on the environment, the demand for environmentally friendly materials is significantly raised in recent years. With the development of polymer fiber industry, researchers began to innovatively use the polymer fiber instead of inorganic fiber to reinforce the same polymer matrix defined as single polymer composites (SPCs), which offers a possible solution for improving recyclability over traditional composites and a strong interface performance by virtue of the same composition between fiber and matrix [1]. The existing results on SPCs and related materials have been already reported in the review papers [2–5] and their references.

The concept of single polymer composites (SPCs) was first described by Capiati and Porter in 1975 [6]. SPCs were also referred to self-reinforced, single-phase, homogeneous, mono-material, homogeneity or homo-composites. SPCs were classified in respect to their composition and usually empowered two subgroups [7]: (i) SPCs from the same polymer (one-constituent SPC) and (ii) SPCs from the same polymer type (two-constituent SPC).

Since Capiati and Porter exploited oriented polyethylene (PE) filaments and PE powder with different melting points to create the first single polymer composites, a variety of processing techniques for single polymer composites have been developed, such as powder impregnation [8], solution impregnation [9,10], hot compaction [11,12], film stacking [13] and bi-component tape technology [14,15]. Some other processing methods have also been investigated, such as injection molding [16] and continuous extrusion [17], but have not yet led to commercial exploitation. The most frequently used techniques are film stacking and hot compaction, in which the chosen matrix film generally has a lower melting point than the fibers, so that only the interleaved film melts. However, the main disadvantage of the techniques is the narrow processing window which is limited to 2–4 °C [18,19]. It is intuitive that the major task of exploiting polymer for SPCs is to

---

* Corresponding author. State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, PR China.

E-mail address: glwen@hnu.edu.cn (G. Wen).

http://dx.doi.org/10.1016/j.polymertesting.2016.06.006

widen the temperature range between the matrix and reinforcement with respect to their softening and melting. The most reported studies are based on the use of polyolefin and polyester materials such as PE-based composites, PP-based composites, PLA-based composites and PET-based composites [4]. To further enlarge the processing temperature window, researchers have also utilized polymers with the same chemical composition but different chemical structures. Devaux and Cazé [20] reinforced LDPE (low-density polyethylene) with UHMWPE (Ultrahigh molecular weight polyethylene) fibers, and the processing window was further enlarged to about 40 °C. PA materials were also chosen to combine them with aramid fiber to extend the family of single polymer composites [21].

In attention to the outstanding recyclability and strong interface adhesion, the impact resistance was widely studied as it was a key advantage of SPCs [22–27]. Therefore, most of the current applications exploited its excellent impact resistance. One of the most well-known polymeric fibers for protective systems is aramid fiber with the commercial name Kevlar®. Although there were studies of the ballistic performance of aramid/thermoset matrix systems [28,29], the available experimental data in open literature for aramid/thermoplastic matrix composites is limited [30] and the aramid/thermoset composite is not an SPC. Moreover, aramid/polyamide systems which can be defined as the category of single polymer composites have not been studied in detail, especially in the aspect of dynamic impact.

A SHPB apparatus is frequently used in the experimental determination of dynamic mechanical properties during the research on fabric reinforced composite. Yang et al. [31] analyzed stress uniformity in split Hopkinson bar test specimens and provided guidelines to assess the validity of experimental data. Song et al. [32] investigated the compressive behavior of woven carbon/epoxy laminate composites under in-plane and out-of-plane loading using a servo-hydraulic test machine (type MTS810 from MTS Systems Corporation, USA) and a developed SHPB apparatus. The results indicated that the stress-strain curves, maximum compressive stress and strain all evolved as strain rate varies.

This study is motivated by the lack of knowledge in the study of single polymer composite made from aramid woven fabric and thermoplastic PA matrix about impact resistance. In this work, high strain rate compression behavior along thickness for the composite is tested and analyzed, which provides a basis for selecting composite composition and lay-up for designing armor with improved impact resistance. The out-of-plane compression properties of the single polymer composites are investigated on SHPB apparatus in the strain rate range of 400–1200/s. Then, the effects of fiber content and strain rate on the high strain rate response are addressed. As a comparison, quasi-static properties are obtained on a universal testing machine. In addition, this work presents an ingenious method for hot compaction technique in the process of sample preparation using DSC and capillary rheometer.

2. Experimental methodology

2.1. Materials

Aramid yarns with a linear density of 1670 dtex and yarn diameter of 0.017 inch are produced by Dupont and used in the studies. The weft and warp yarns are woven into plain weave fabric of Kevlar®29 240-1500D (240 g/m^2). PA6®3508 matrix is also produced by Dupont and processed into films with a density of 1.14 g/cm^3 and a thickness of 0.3 mm. Silicone oil KF-96 with a flash point of 300 °C produced by Shin-Etsu Chemical Co. Ltd of Japan is used as release agent in the process of production for the convenience of demolding. To avoid any risk of moisture, the prepared fiber and PA films are kept in an oven at 90 °C for 4 h prior to be transferred in the mold.

2.2. Composite processing

The bulk composites are prepared as laminate panels with a size of 300 × 300 mm and a thickness of 5 mm by film stacking through a subsequent hot pressing process. Firstly, lay-ups are started and finished with a thin film of PA6 on the outer surface and placed in a vacuum aluminum foil bag for vacuum (−80 kPa) packing. Secondly, the vacuum aluminum foil bag with lay-ups is assembled in the picture frame mold as schematically illustrated in Fig. 1(a). Finally, the assembly is inserted into the hot press apparatus as shown in Fig. 1(b) and heated to 245 °C at a rate of 10 °C/min. After a dwell time of 25 min at 245 °C and a constant pressure of 1.5 MPa, the press is unloaded and cooled to 80 °C for demolding.

In this work, specimens with three fiber contents are fabricated as three types of layers in the stacking sequence of woven fabric inside the PA films and the fabrication process are graphically illustrated in Fig. 2. That is, the fiber content is varied by laying one or two films per fabric layer. The theoretical weight fractions of the fiber for the composite laminates can be estimated by the following equation:

$$W_f = \frac{n_f \rho_f}{n_f \rho_f + n_m \rho_m} \times 100\%, \ \rho_m = \frac{\rho}{h_m} \tag{1}$$

where n_f and n_m are the numbers, ρ_f and ρ_m stand for the surface densities of the fabric and PA film, ρ is the density and h_m is the thickness of the PA film, respectively.

The theoretical density of the composite laminates can be estimated by Equation (2) as follows,

$$\rho_c = \frac{n_f \rho_f + n_m \rho_m}{h_c} \tag{2}$$

where h_c is the final thickness of the composite laminate. The details of characteristics of the composite laminates are summarized as shown in Table 1. The following nomenclature is used: W_1, W_2 and W_3 for the three fiber contents composite laminates in this study.

3. Testing

3.1. DSC

The chosen matrix film generally has a lower melting point than the fibers, so that only the interleaved film melts in the process of hot compaction. In order to prepare SPCs, the processing temperature window should be determined. A differential scanning calorimeter (type of 200 F3 Maia from NETZSCH, Germany) is employed for thermal analysis of aramid fiber and PA6 film. The extracted samples, with a weight of 5–7 mg, are heated from the room temperature to 400 °C at a rate of 10 °C/min and an argon flow of 50 ml/min is used. The melting temperature is determined at the maximum of the heat capacity versus temperature.

3.2. Rheology

Rheological properties of PA6 matrix are very sensitive to temperature so that it is significant for impregnation of aramid fabric. Therefore, the rheological measurements of the PA6 film should be applied to further determine the lower limit of the flow temperature. A capillary rheometer (type of XLY-IIfrom Science and education instrument factory of Jilin University, China) was used in this