Composite Structures 161 (2017) 85–92

Contents lists available at ScienceDirect

Composite Structures

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

The static and dynamic response of CFRP tube reinforced polyurethane

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ARTICLE INFO

Article history:
Received 3 November 2016
Accepted 12 November 2016
Available online 14 November 2016

Keywords:
Carbon fibre
Dynamic
Energy absorption
Mechanical testing
Polyurethane
Reinforcement
Thermoset
Thermoplastic

ABSTRACT

This paper presents an investigation on the mechanical properties of thermosetting polyurethane (TSPU) and thermoplastic polyurethane (TPU) under quasi-static and low velocity impact (LVI) loading. Hollow glass microspheres were added at different volume percentages to the TSPU to decrease the density and to investigate the effect on the mechanical properties. Incorporating the fillers leads to the development of a stepwise graded foam, which has been shown to yield more constant plateau stress levels under dynamic loading. The work was extended to investigate reinforcing the TSPU and the TPU matrix with carbon fibre reinforced plastic (CFRP) tubes, providing a higher load-bearing capacity under static loading. Reinforcing the syntactic TSPU resulted in a 47.7% increase in specific energy absorption (SEA), with the average value reaching 56.28 kJ/kg. The specific compressive strength for the reinforced TSPU was also improved under quasi-static loading, where a 65% increase was observed, relative to the unreinforced TSPU. For the reinforced TPU significant improvements were seen under dynamic loading conditions, relative to the unreinforced TPU, with increases in plateau stress levels of 629% and 452% at strain levels of 25% and 50%, respectively.

1. Introduction

Polyurethane is a versatile and widely used polymer that is available in the form of either thermoplastic polyurethane (TPU) or thermosetting polyurethane (TSPU). The polyurethanes (PU) industry is a rapidly expanding business that currently produce some 12 million metric tons of PU raw material annually, with revenues forecast to reach US 74 billion by the year 2022 [1]. As a result of the wide variety of polyols and isocyanates that are available as raw materials, the structure of the polymer can be modified in order to satisfy specific design requirements for a given application. Subsequently, these polymers have been widely used in applications as diverse as biomaterials for implants [2] as well as in electronic and technological applications [3,4].

Hollow glass microspheres (HGM) are widely used as fillers of polymer matrix syntactic foams (PSF), as a result of their low heat conductivity and density [5]. PSF are a class of lightweight materials that consist of thin-walled hollow particles, dispersed within a polymer material. These materials are popular due to their ability to provide high specific mechanical characteristics, i.e. specific compressive strength and stiffness, as well as combined with the relative ease of manufacturing associated with such foams. It has been illustrated in several studies that low density polyurethane foams filled with hollow microspheres can enhance the strength and elastic modulus of foams in compression [5–9]. Despite the wide experience accumulated in the field of syntactic foams, it is nevertheless a topical area of study, due to the possibility to tailor the material properties by varying the size, wall thickness and volume-fraction.

In addition to the syntactic foams, one may wish to modify the distribution of the particles in order to enhance the mechanical behaviour of the foams. This may come in the form of a graded structure. The aim of a graded structure is to control the compression deformation behaviour of the material. It has been shown in several studies [10–13] that graded structures can outperform their monolithic counterparts. Graded materials have their composition, density or microstructure changed in the through-thickness direction of the structure. Particularly for dynamic applications, these structures are attractive due to the progressive response under dynamic loading.

Furthermore, reinforcements in terms of embedding composite tubes in foams can be used in order to further enhance the mechanical properties of such composite structures. There have been several studies reported on the axial crushing behaviour of composite and metallic tubes [14–21]. The purpose of crush tubes

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http://dx.doi.org/10.1016/j.compstruct.2016.11.043
0263-8223/

is to absorb and convert kinetic energy into gross plastic deformations under severe loading condition. Alia et al. [22] reported the findings of low density polymer foams reinforced with T700 CFRP tubes, with promising results. The specific energy absorption (SEA) was shown to increase with decreasing inner diameter to thickness (D/t) ratio and it was shown that a tube with a D/t ratio of 6.3 provided the highest energy absorption per unit mass.

The aim of this research was to combine the aforementioned parameters, i.e. fillers, tubes and functionally graded foams (FGF), into one structure, to optimise the structural response under static and dynamic loading conditions. To date, there has been limited research on such structures. These materials may be suited to a number of energy-absorbing structures, such as those employed in automobiles, aircraft and ships, where crash safety is of great importance. In order to optimise the mechanical properties of syntactic TSPU (casting resin), the volume fraction of HGMs is varied systematically. Furthermore, to control the load during compression in energy absorbing structures, developments in the grading of the syntactic foams are made, resulting in FGF. The work was extended via the introduction of CFRP tubes into the TSPU (syntactic and non-syntactic) to increase in SEA for static and dynamic applications, with comparisons made against CFRP reinforced polyether TPU.

2. Experimental methodology

2.1. Manufacturing

TSPU, a highly cross-linked polymer, was manufactured using vacuum assisted resin transfer moulding (VARTM). The TSPU has two parts, the resin (Part A) – the formulated polyol was mixed with hollow glass microspheres (K20 series, $\phi = 30 - -115$ µm, $\rho = 0.2$ g/cc) [23] for several minutes to ensure that the microspheres were well distributed, after which the hardener (Part B) – the isocyanate – was added to the mixture. The mix ratio of both components was 100:100 g/g. The resin was transferred through a channel and into the 200 × 200 mm mould with a depth of 20 mm. However, prior to this a vacuum pump was attached to the outlets, to minimise the amount of trapped air and enabling the resin to flow into the mould by introducing a pressure difference. Fig. 1 shows the density variations of the syntactic TSPU as a function of the percentage of microspheres within the matrix. M0 is defined as the pure TSPU, without any microspheres and M1–M12 refer to the syntactic TSPU with varying levels of density.

The volume fraction of the microspheres is calculated using the following equation,

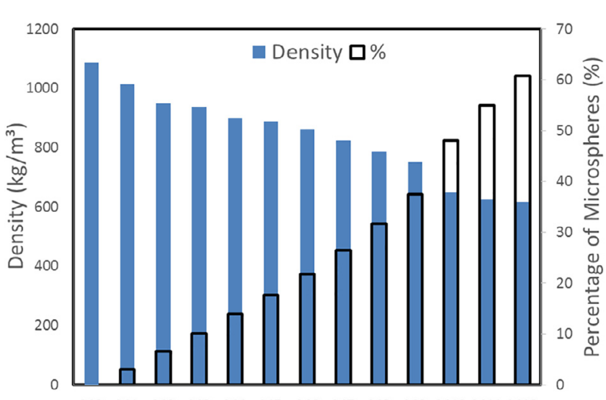


Fig. 1. Variation of hollow glass microspheres (%, volume) and density (kg/m³) of the syntactic TSPU.

$$\frac{W_{SF}}{V_{SF}} = \rho_{GM} \cdot (f_{GM}) + \rho_{PU} \cdot (1 - f_{GM}) \quad (1)$$

where W_{SF} and V_{SF} are the measured weight and volume of the syntactic foam. ρ_{GM} and ρ_{PU} represent the densities of the glass microspheres and the resin, respectively. The density of the TSPU resin is approximately 1087 kg/m^3. Rearranging Eq. (1) provides the volume fraction of the microspheres (f_{GM}) as

$$f_{GM} = \frac{\rho_{PU} - \rho_{SF}}{\rho_{PU} - \rho_{GM}} \quad (2)$$

where ρ_{SF} represents the density of the syntactic foam.

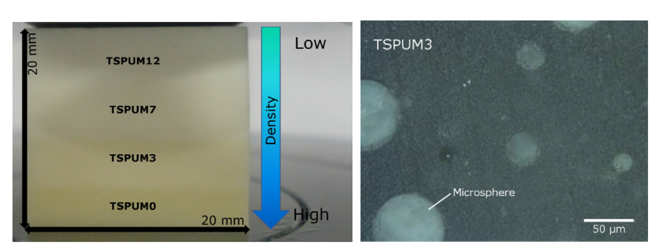
During the manufacturing process one cannot fully ensure the hollow microspheres are fracture free. Careful processing is advisable but may not completely eradicate this issue. Fracturing of the spheres would open up their cavity, which could subsequently be filled with the resin. Therefore, the volume fraction of microspheres can only be provided as an approximation.

Fig. 2a presents an example (TSPUG1) of one of the graded foams used in this study, with a four-density variation at a 5 mm depth increment. Fig. 2b shows an optical micrograph taken on the surface of the composite with a surface finish of approximately 5 µm, which illustrates the dispersion of the microspheres within the TSPU matrix. The investigation on the stepwise graded foams i.e. G1 and G2, uses the different densities for the individual foams as detailed in Table 1.

TPU is a linear segmented block copolymer consisting of hard and soft segments that can be moulded when heated before returning to a solid phase when cooled. Specimens based on the polyether grade TPU (Desmopan DP 9852 [24]) were used in this study and manufactured using a hot press. The TPU pellets were pre-dried at 110 °C for 3 h and placed into a mould that was initially heated to 50 °C. In order to prevent the sample from sticking to the mould, a silicon based grease was applied on the interior surface of the 150 mm by 150 mm mould. A pressure of 350 kPa and a temperature of 220 °C were maintained for 25 min. The specimen was then cooled at room temperature and removed from the mould when the temperature was below 50 °C. The specimens were then washed with distilled water, followed by washing with ethanol in order to minimise contamination. The TPU panels had a density of 1150 kg/m³. For the reinforcement, T700 unidirectional carbon fibre tubes, with a density of 1600 kg/m³ and an outer diameter of 10 mm (D/t ratio = 6.3), were embedded within the TSPU and TPU matrix. The arrangement of the tubes in the TSPU and TPU is illustrated in Fig. 3.

2.2. Mechanical testing

Compression tests on the TPU and TSPU specimens were carried out on a 100 kN Instron 4505 universal servo hydraulic testing machine. Tests were performed with loading axis orientated in



(a) TSPUG1 cross-section (b) Optical micrograph

Fig. 2. (a) Example of the cross section of stepwise graded foam (TSPUG1), with density variation through-thickness and (b) optical micrograph of TSPUM3 illustrating the embedding of glass microspheres in the TSPU matrix.