Composites: Part B xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Composites: Part B

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

An hysteresis energy-based synthesis of fully reversed axial fatigue behaviour of different polypropylene composites

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ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form 13 December 2013
Accepted 14 January 2014
Available online xxxx

Keywords:
A. Glass fibres
B. Fatigue
E. Injection moulding
Hysteresis energy

ABSTRACT

In this paper the hysteresis energy density per cycle was considered as fatigue damage index to rationalise in a single scatter band the fatigue behaviour of short glass fibre reinforced polypropylene (30 wt% 1-mm-long glass fibre), long glass fibre reinforced polypropylene (30 wt% 10-mm-long glass fibre) and 42 wt% calcium carbonate filled polypropylene. Moreover the nature of such a mechanical energy was investigated to establish to which extent dissipation is due to creep strains and it was found that hysteresis energy dissipated in a unit volume of material per cycle due to visco-elasticity is negligible with respect to the total hysteresis energy.

1. Introduction

The growing number of applications of short fibre reinforced- or filled-plastics (SFRP or FP, respectively) under cyclic loading in the last decades led to an increased interest in understanding their fatigue behaviour in terms of several key parameters as the influence of type of matrix (thermoplastics and thermosets) [1], reinforcements (material and fibre architecture), environmental parameters such as temperature and aging [1–5], loading parameters such as test frequency [1,6,7], mean stress [4–6,8] and variable amplitude fatigue [9], the presence of notches [4], the effect of mean fibre orientation [5,10] and specimen's thickness [5].

As an example Zago and Springer [6] synthesised the influence of mean stress, frequency, fibre content and fibre orientation by means of a master curve obtained by normalising the stress amplitude with the ultimate tensile stress of the relevant material configuration. On the other hand, the influence of load test frequency was rationalised by Bernasconi and Kulin [7] by means of a frequency superposition method, based on the correlation of the applied stress with the average temperature increase due to the hysteretic self heating and the strain rate by means of the Larson Miller parameter [11]. A modified Gerber equation to account for the creep-fatigue interaction at different load ratios was proposed by Mallick and Zhou [8], to synthesise the effect of mean stress on the fatigue strength of 33% weight short *E*-glass fibre reinforced polyamide-6,6 composite. The influence of mean fibre orientation on fatigue strength of 30 wt% short glass fibre reinforced Polyamide 6 was investigated by Bernasconi et al [10], who proposed for design purposes a single master fatigue curve by normalising the maximum stress with respect to the ultimate tensile stress of the relevant material configuration. Finally, the Tsai–Hill criterion, modified to account for cycling loading, was proposed by De Monte et al [5] to synthesise the influence of mean fibre orientation on 35 wt% short glass fibre reinforced polyamide 6.6.

Several works addressed the fatigue crack propagation in SFRP by using pre-cracked specimens. The influence of different parameters were investigated such as type of matrix [1,12], type of reinforcement [1,12–14], fibre content [1,12,15] and orientation [16], mean load [12,16], load test frequency [12,15,16].

Although it is one of the key-parameters recalled above, a reduced attention was paid to analyse the influence of reinforcement or filler on the *fatigue* behaviour of plastics. In fact the influence of this parameter was studied in depth mainly in the case of *elastic* as well as *static* properties of SFRPs and generally it was found an increment on elastic modulus, static strength and fracture toughness by increasing the Weight Average Fibre Length (WAFL) [17–21]. Usually the elastic modulus and the static strength was successfully correlated to the WAFL by using a modified Kelly–Tyson model [17,18] or a modified rule of mixture [19,20].

The effect of WAFL and matrix flexibility on *fatigue* was analysed by Hitchen et al [22] on random short carbon fibre/epoxy composite containing 1, 5 or 15 mm long fibres and, for the sole 5-mm-long fibres, the matrix was either the standard or a

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http://dx.doi.org/10.1016/j.compositesb.2014.01.027
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flexibilised epoxy. In the case of standard matrix, they found that despite the considerable scatter in the fatigue data, the longer fatigue lives are obtained for specimens containing longer fibres at a given load level. Nevertheless, by considering the maximum strain reached during the fatigue tests as fatigue damage index, the authors observed that the influence of fibre length can be synthesised in a single scatter band. Conversely, the maximum strain was not able to rationalise the influence of the flexibiliser on fatigue behaviour of 5-mm-long fibres composites. Different results were found in a recent experimental paper of Rohde et al [23]. The authors analysed the influence of fibre length on glass-fibre reinforced Polyamide 66 composites under static and fatigue loads, by considering two different types of process (standard injection moulding and Injection Moulding Compounder, IMC) and two different fibre lengths for each process. In the case of standard injection moulding, in spite of an increase of the WAFL of a factor about 2.7 (from 0.5 mm to 1.34 mm) they found a 5% increment in the static tensile strength (104 MPa and 109 MPa, respectively). On the contrary, in the case of specimens made by the IMC process and having WAFL equal to 8.5 mm and 12.91 mm, the authors measured a tensile static strength equal to 134 MPa and 130 MPa, respectively. A no clear influence of the fibre length was observed by the authors also in the case of fatigue tests. They performed stepwise load-increasing tests and they found that 1.34 mm – WAFL specimens fail earlier than the other compounds and, for a given applied stress amplitude, they observed only a 5% increment in terms of number of cycles to failure by increasing WAFL from 8.5 to 12.91. A possible explanation for these opposite experimental results can be found following Huang and Talreja [24], who analysed the micro-cracking in SFRP and subsequent damage evolution and they showed that if the interface is strong and/or the matrix is ductile, the matrix plastic deformation and the subsequent cracking near the stress concentration point (typically at the fibre end) relieve the stress so that debonding is suppressed. Under such circumstances the matrix micro-cracking becomes the governing mechanism and therefore the influence of fibre length on fatigue strength can be considered negligible.

In an attempt to provide a contribution on the possibility to rationalise the high cycle fatigue behaviour of plastics for different reinforcements or fillers, in the present paper the fatigue behaviour of short glass fibre reinforced polypropylene (PP) (30 wt% 1-mm-long glass fibre), long glass fibre reinforced PP (30 wt% 10-mm-long glass fibre) and 42 wt% calcium carbonate filled PP was investigated at room temperature (RT). All fatigue data were collapsed together in to a single scatter band in terms of the hysteresis energy expended in a unit volume of material per cycle, according to energy-based concepts originally proposed by Ellyin [25]. Finally the nature of such a mechanical energy was investigated to establish to which extent dissipation is due to creep strains and it was found that hysteresis energy dissipated in a unit volume of material per cycle due to visco-elasticity is negligible with respect to the total hysteresis energy.

2. The hysteresis energy density as fatigue damage index

In the case of *metals*, Ellyin [25] pointed out that of the total energy expended in a unit volume of material per cycle W, only part is stored in the form of internal energy, ΔU, and is responsible for fatigue damage accumulation (dislocation movements along slip planes and damage leading to crack initiation and subsequent propagation). The remaining part, Q, is dissipated as heat, which induces some temperature increase during fatigue testing. Ellyin underlined the experimental difficulties for measuring the thermal energy and assumed W as fatigue damage indicator. This drawback was recently overcome by Meneghetti [26], who showed that the energy dissipated to the surroundings as heat in unit volume of material per cycle, Q, can be used as a fatigue damage indicator for metals and SFRP [27]. Ellyin and El-Kadi [28] proposed a fatigue failure criterion for unidirectional continuous fibre reinforced laminas based on the elastic strain energy density. Starting from the experimental evidence that a major portion of the life of a composite material involves sub-critical damage accumulation characterised by matrix cracking, fibre-matrix debonding, delamination and fibre failure, they stated that a precise characterisation of a composite material would require a sufficient knowledge of the way the energy dissipated as damage in the inhomogeneous material is being accumulated. The authors [28] suggested to use the elastic strain energy density as fatigue damage index to take into account such a complex damage process. Following Ellyin [25], the sum of the dissipated strain energy density and the amplitude of the elastic strain energy density, called total strain energy density, was successfully proposed by Tao and Xia, to synthesise the fatigue data obtained by carrying out axial stress- and axial strain-controlled tests [29] as well as cyclic shear and proportional axial shear fatigue tests with mean strains [30] on an epoxy resin. In the present paper it is investigated to which extent the hysteresis energy expended in a unit volume of material per cycle W could also be used as a damage parameter for discontinuous reinforced or filled plastics.

3. Materials and testing methods

In this paper fatigue tests were carried out on different PP compounds: 30 wt% glass fibre with a nominal fibre length of 1 mm (30 GF 1), 30 wt% glass fibre with a nominal fibre length of 10 mm (30 GF 10) and 42 wt% Calcium Carbonate (CC) filler. 30 GF 1 and 30 GF 10 samples were manufactured by injection moulding. Concerning the PP specimens filled by CC, two different manufacturing conditions were considered: a first group of specimens (42 CC Type A) was obtained by cutting the material from a rear tub of a washing machine manufactured by injection moulding and then the coupons were machined to the final geometry shown in Fig. 1. Conversely, for a second group of specimens (42 CC Type B) the same geometry was obtained directly by injection moulding. For each material configuration, three static tests were carried-out at RT, by imposing a displacement rate equal to 5 mm/min, according to ASTM D638 standard [31].

The fatigue tests were carried out by imposing a sinusoidal wave form characterised by a nominal stress ratio R (defined as the ratio between the minimum and the maximum stress) equal to -1. Test frequencies between 1 and 22 Hz were adopted, depending on the applied stress level. In order to maintain the surface temperature of the specimen in the range from 20 to 30 °C, a blower was used to cool the samples and 0.127 mm diameter copper-constantan thermocouples were fixed on the back face of the specimens by means of a silver-loaded conductive epoxy glue. Temperature signals generated by the thermocouples were acquired by means of data logger Agilent Technologies HP 34970A operating at a maximum sample frequency of 22 Hz. During fatigue tests the hysteresis loops were measured by using the signals of the load cell and a MTS extensometer having gauge length of 25 mm. Both static and fatigue tests were carried out on specimen's geometry shown in Fig. 1. Finally some creep tests were carried-out at RT on 42 CC Type A specimens by imposing a constant load for 48 h and by monitoring the creep strain with the same MTS extensometer adopted for fatigue tests. After that, in order to evaluate the recovery capacity of the material, the load was removed and the strain was recorded for additional 48 h. All tests described previously were carried out on a MTS Minibionix servo-hydraulic test machine equipped with a 15 kN load cell.

Please cite this article in press as: Meneghetti G et al. An hysteresis energy-based synthesis of fully reversed axial fatigue behaviour of different polypropylene composites. Composites: Part B (2014), http://dx.doi.org/10.1016/j.compositesb.2014.01.027