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Influence of moisture on the fatigue behaviour of a woven thermoplastic composite used for automotive application

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ABSTRACT

Effect of moisture conditions on the fatigue lives of woven glass-fibre-reinforced polyamide 6,6 composite was investigated. Fatigue tests were conducted at a stress ratio of $R = 0.1$ on specimens of different stacking sequences, namely $[(0/90)_3]$, $[(90/0)_3]$ and $[(\pm 45)_3]$ and different moisture contents (RH0, RH50 and RH100). Although moisture content highly affects the fatigue life for high stress levels, this effect tends to lessen for lower stress levels. As this phenomenon was unexpected, additional fatigue tests in climatic chamber were performed. These tests support initial results and confirm the fact that the effect of moisture tend to decrease for low stress levels. In addition, this study proposes an enhanced fatigue life model to predict accurately the fatigue lives of this material for any moisture content and fibre orientation. This model shows a good correlation with experimental data.

1. Introduction

The automotive industry shows increasing interest for continuous glass fibre composites with thermoplastic matrix. Even if thermoplastic polymers provide the advantage to be recyclable, some of them present the major drawback to be sensitive to water [1–5]. It is the case of PA6,6 [6–10], mostly used in automotive structural parts. During their service life, these parts undergo cyclic loading in various temperature and moisture conditions. It is thus important to be able to predict the fatigue behaviour of this type of composite for design purpose.

The fatigue behaviour of short glass fibre reinforced PA6,6 for different mold flow directions and temperatures has already been modelled in previous studies. Mortazavian et al. [11] use a life prediction model based on strength degradation, previously developed and tested by Epaarachchi and Clausen [12] for non-woven glass fibre reinforced polymer (GFRP). Mortazavian et al. [11] highlight the ability of this model to predict fatigue life of short glass fibre/PA6,6 composite for different temperatures, stress ratios and directions with respect to the mold flow direction with accuracy. Other authors have also used this model to predict fatigue life of continuous fibre composites, mainly because of its ease and speed of use [13–16].

The influence of moisture on the behaviour of continuous fibre reinforced with thermosetting resin has been reported in the literature [17–25]. Hu et al. [17] have studied the tension-tension fatigue behaviour of both UD glass/polydicyclopentadiene laminates and UD glass/epoxy laminates after ageing in salt water. They have showed that the slope of the S-N curves decreased with ageing time. This result indicates that ageing has a greater influence on low-cycle fatigue than on high-cycle fatigue. Fatigue tests were instrumented with acoustic emission in order to study the damage scenario developed within the materials. Thus, it has been showed that the degradation of glass fibre was determined primarily by ageing time, while the interface degradation was affected primarily by the moisture level in the matrix. Patel and Case [20] have studied the influence of moisture on the fatigue life of a graphite/epoxy woven composite material. This study has shown that fatigue life of this type of composite is not affected by moisture, although damage accumulation process is different. A residual-strength-based life prediction model is used to estimate the fatigue life for all of the environments considered.

The present work is focused on a woven glass-fibre-reinforced composite with a polyamide 6,6 matrix. To our knowledge, there is no publication dealing with the fatigue behaviour of such a continuous fibre/thermoplastic composite so far. The aim is to investigate the influence of the moisture content on the fatigue life of this material. Thus, three moisture contents were studied, referred as RH0, RH50 and RH100 corresponding respectively to a dry-as-moulded, reference (ambient humidity) and water-saturated state. In order to study the influence of the fabric orientation, three layups were studied, designated as $[(0/90)_3]$, $[(90/0)_3]$ and $[(\pm 45)_3]$. S-N curves were established for all layups in every moisture conditions. Moreover, some complementary fatigue tests were done in a climatic chamber with humidity regulation to evaluate the influence of the test environment on the fatigue life. The RH50, $[(0/90)_3]$ samples were used to identify the material parameters of the

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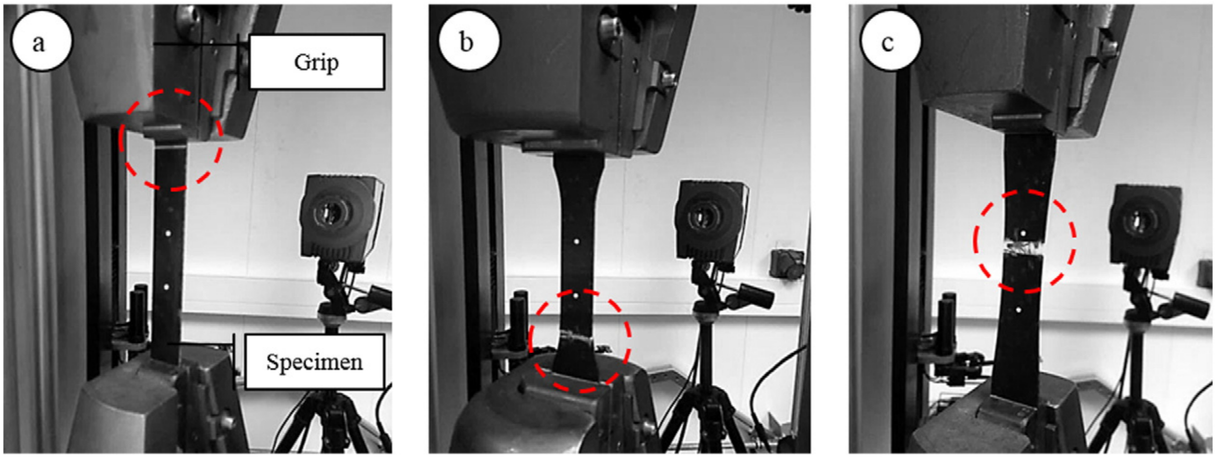

Fig. 1. Failure location during fatigue test for (a) rectangular specimen (b) dumbbell specimen (c) dogbone specimen.

fatigue life model proposed by Ref. [12]. The objective is to model the behaviour of the woven glass-fibre-reinforced PA6,6 composite for any combination between moisture conditions and layups, by using only one S-N curve as a reference.

2. Materials and methods

2.1. Tested material

The composite material studied is made of three plies of a 2/2 twill woven glass fabric impregnated with polyamide 6,6 resin. The glass fibre fabric has a weight of 600 g/m^2 and a warp to weft ratio of 50/50. The fibre mass fraction (m_f) is equal to 0.63 and the void content is below 1%. The resulting composite plates are characterised by a density of 1.78 g/cm^3. The material is provided as plates of 1.53 mm thick and coupons are cut using water jet cutting technique. It has been checked that this technique has no significant influence on the material moisture content. The specimen edges were polished to remove mechanical damage caused by the cutting. The influence of fabric orientation on mechanical properties is studied using three different stacking sequences. The first one, referred as $[(0/90)_3]$, has the warp direction of each ply oriented at 0° from the tensile axis (x axis). The second one, referred as $[(90/0)_3]$, has the weft direction of each ply oriented at 0° from the tensile axis (x axis). Finally, the $[(\pm 45)_3]$ has the warp direction of each ply oriented alternately at +45° and −45° from the tensile axis.

2.2. Conditionings

Three conditionings were studied in order to evaluate the influence of moisture on the fatigue behaviour of the composite: RH0, RH50 and RH100. Conditioning was done by the material supplier by following the standard ISO 1110. Whereas RH0 corresponds to the dry-as-moulded state of the composite material, RH50 and RH100 were conditioned in a climatic chamber until weight stabilization. The influence of moisture content on thermal and monotonic tensile properties has already been investigated in a previous study [26].

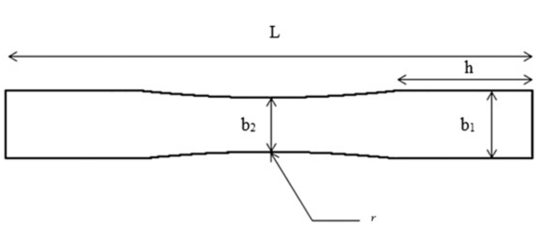

Fig. 2. Dimensions specification of dogbone specimen.

2.3. Experimental procedure

2.3.1. Fatigue tests

Fatigue tests were performed by using an INSTRON 8501 servo-hydraulic machine. The jaws of test machine clamp 40 mm of each specimen extremity and 80 grit sand papers were used in the jaws to improve clamping. Constant amplitude loads were applied in a sinusoidal waveform at the frequency of 1 Hz in order to limit self-generated heating in the specimen. The stress ratio (R), i.e. ratio between minimum (σ_{min}) and maximum (σ_{max}) stresses, was equal to 0.1 for all tests.

2.3.2. Fractography

Fracture surface observations were performed on a JEOL 7000F field emissions gun scanning electron microscope (FEG-SEM). Specimens were coated with gold/palladium by vacuum metallisation.

2.3.3. Fatigue life model

The fatigue life model used in this study is proposed by Epaarachchi and Clausen [12]. This model allows the prediction of the fatigue life using a very limited amount of experimental data. The model is based on the hypothesis that the material strength undergoes a continuous decay, following a power law as proposed by Caprino and D'Amore [27] (Eq. (1))

$$\frac{d\sigma_n}{dn} = -a \cdot n^{-b} \tag{1}$$

where σ_n is the residual strength after n cycles, b is a positive definite constant, dependant on the material and the mode of loading, a is assumed to increase linearly with the stress amplitude. Finally, the model is presented in Eq. (2) [12].

$$N_f = \left(1 + \left(\frac{\sigma_u}{\sigma_{max}} - 1\right) \frac{f^\beta}{\alpha(1-R)^{\lambda - R|\sin\theta|}} \left(\frac{\sigma_u}{\sigma_{max}}\right)^{\lambda - 1 - R|\sin\theta|}\right)^{1/\beta} \tag{2}$$

where N_f is the fatigue life, σ_{max} is the maximum fatigue stress, σ_u is the ultimate tensile strength, f is the frequency, R is the stress ratio and θ is the smallest angle between the loading axis and the fibres. The parameter λ is assumed to be equal to 1.6 according to Epaarachchi et al. [12]. Hence, α and β are the only two material parameters that need to be

Table 1
Dimensions of used dogbone specimen (in mm).

L	h	b_1	b_2	r
200	50	25.4	20	464.31