Composite Structures 134 (2015) 900–904

Contents lists available at ScienceDirect

Composite Structures

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

Infrared thermography to evaluate thermoplastic composites under bending load

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ARTICLE INFO

Article history:
Available online 3 September 2015

Keywords:
Infrared thermography
Thermo-elastic effects
Thermoplastic composites
Cyclic bending tests

ABSTRACT

Thermoplastic matrix-based composites are becoming ever more popular due to their many advantages over both metals and thermoset matrix-based composites. In particular, they can be tailored by the addition of a compatibilizing agent to the matrix, which allows to create a multitude of materials. Of course, each of these materials requires characterization for an appropriate exploitation. In this context, infrared thermography represents a viable inspection means since it is non-contact, non-intrusive and can be used to monitor the entire existence of a product, from its manufacturing process to completion as well as in-service life. In this work, several composite materials based on a polypropylene matrix, which may be neat, or modified by addition of a certain amount of a specific compatibilizing agent, and reinforced with glass, or jute, woven fibres are considered and subjected to cyclic bending tests. Infrared thermography is used for monitoring the bending event.

1. Introduction

Composite materials are increasingly used in an ever more wide number of application fields such as in the transport industry, in civil infrastructures, in chemical equipments, as well in the fabrication of many objects for use in daily life. Their success is mainly due to their high strength-to-weight ratio, easy formability, and other properties that make them preferable to metals and other conventional engineering materials. Nowadays, particular attention are gaining composites based on a thermoplastic matrix because of their many advantages compared with their thermoset counterparts, in terms of: potential recyclability after life-cycle, chemical and environmental resistance, reduced moisture absorption and, usually, faster production as well as reduced processes costs [1]. In addition, a good-to-impact performance material can be tailored by managing interface strength; in fact, the interface strength between fibres and matrix plays a key role in dissipating energy during an impact [2].

Besides the many advantages, also thermoplastic composites pose some problems, which are common to all composites, when attempting to establish duration and fatigue-life criteria. In fact, the duration of a metallic component is dependent on the possible formation of cracks and their growth. Metal fracture mechanics is often adequate to predict the size of critical flaws and, as a consequence, to establish rejection/acceptance criteria on the basis of the designer requirements. On the contrary, composites are broadly inhomogeneous and behave in a complex way which is difficult to be modelled, so that, the availability of experimental data is of great importance.

In this context, infrared thermography represents a useful investigation tool. Indeed, infrared thermography proved already its usefulness within a twofold objective of surface thermal mapping when the specimen is under load (bending, or impact) and as non destructive evaluation (NDE) technique. However, the investigation has regarded mostly composites based on a thermoset matrix [3–5] with little attention to those involving a thermoplastic matrix [6].

The aim of the present paper is to get more information on thermoplastic composites under cyclic bending, in particular, to ascertain whether it is possible to get, in a simple way, information which may be exploited for their characterization.

2. Theoretical considerations

The thermo-elastic effect was first conceived by Lord Kelvin (W. Thomson) in 1878 [7]. Many years later, in 1956 [8], Biot

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http://dx.doi.org/10.1016/j.compstruct.2015.08.120
0263-8223/

performed a thermodynamic analysis and formulated the classical thermo-elastic equation, which expresses the change in temperature (T) of a solid in terms of the change in the sum of the principal stresses (σ). The change in temperature is generally used to perform thermo-elastic stress analysis tests (TSA) [9–12]. The temperature variation, under reversible and adiabatic conditions (i.e., in the elastic regime and neglecting heat transfer within the body and to the environment), for isotropic materials can be written as:

$$\Delta T = -KT_a\Delta\sigma \tag{1}$$

where T_a is the absolute body temperature, $\Delta\sigma$ is the mean stress amplitude, and K is the material thermo-elastic constant. Eq. (1) relates the temperature local variations to the volume variations. In particular, under adiabatic conditions, positive dilatation (tension) entails cooling of the material and vice versa. In metals, the thermo-elastic limit is generally assumed [13] as an indication for the yielding point. In orthotropic materials as fibre-reinforced polymers (FRP) Eq. (1) modifies as [10]:

$$\Delta T = -\frac{T_a}{\rho c_p}(\alpha_1\Delta\sigma_1 + \alpha_2\Delta\sigma_2) \tag{2}$$

with α_1 and α_2 the thermal expansion coefficients along the principal material directions. Under certain conditions when the composite is made of plain weave fabric layers laid up to produce a symmetric laminate, the thermo-elastic response can be considered as originating from the isotropic surface layer [12], making possible the use of the simple Eq. (1).

In general, thermo-elastic effects are associated with the TSA technique whose purpose being to monitor the progression of damage in specific conditions, such as in presence of notched specimens under cyclic tension–compression tests. Owing to bending tests, Luong [14] reports on the use of infrared thermography for detecting the onset of intrinsic dissipation, or damage indicator, owing to the thermo-mechanical coupling. The adopted procedure was to acquiring a thermal image after a fixed number of cycles. In all these cases the analysis was driven towards the thermoplastic phase in which the temperature variation is significant and then easy to be measured. A more difficult point is to deal with measurements of temperature variations experienced by the material during the elastic phase i.e., thermo-elastic effects.

A way to exploit thermo-elastic effects is through monitoring of sound specimens during either cyclic bending, or transient loading like impact tests [3–6]. Under cyclic bending the material undertakes tension and/or compression with cooling/warming effects involved; the temperature variations follow the bending moment trend as depicted in Fig. 1. Then it is possible to acquire information on the material characteristics by simply monitoring the thermo-elastic effects.

A question which may arise is if and how material properties interfere with thermo-elastic effects and, in particular, if it is possible to discriminate any difference induced in the fibre and/or in the matrix by simply visualizing thermo-elastic effects. In light of these considerations, the attention of this work is focused on the use of an infrared imaging device for monitoring the thermal response, under cyclic bending tests, of different types of thermoplastic composites involving change of matrix and of fibres.

3. Experimental investigation

3.1. Description of specimens

Several different specimens were fabricated involving changes of matrix and fibres. In particular, the basic matrix is made of polypropylene (PP grade MA712 from Unipetrol – Czech Republic with MFI = 12 g/10 min), pure or modified with the addition of a given percentage (2–5% by weight) of a common coupling agent, polypropylene grafted maleic anhydride (PP-g-MA) that is commercialized under the trade name of Polybond 3200 (MFI 115 g/10 min, 1 wt% maleic anhydride, from Chemtura). The reinforcement is made of two types of fibres. One includes plain weave type woven glass fabric (E-type glass fibres having density of 2.54 g/cm^3) with a specific mass of 204 g/m^2. The other one jute plain weave type fabric with a specific mass of 250 g/m^2 and furnished by Deyute (Alicante, Spain). Specific details of investigated specimens in terms of code, sizes and composition are summarized in the following Table 1.

3.2. Testing setup and procedure

Cyclic bending tests are performed with the cantilever beam specimen clamped on the bottom side (fixture) and free to bend under the cyclic harmonic force applied at the opposite end. The bending is operated with a machine which allows changing of both bending frequency and specimen deflection. The infrared camera is positioned to see one surface of the specimen. A sketch of the test setup is shown in Fig. 2.

The used infrared camera is the SC6000 (Flir systems), which is equipped with a QWIP detector, working in the 8–9 μm infrared band, NEDT < 35 mK, spatial resolution 640 × 512 pixels full frame

Table 1
Investigated specimens.

Code	Width (mm)	Length (mm)	Thickness (mm)	Composition (Matrix – reinforcement)
P_G	25	125	3.0	Neat PP – woven glass fibres
P_J	25	125	3.8	Neat PP – woven jute fibres
P_JC_2	25	125	3.8	Modified PP (2 wt% PP-g-MA) Woven jute fibres
P_JC_5	25	125	3.8	Modified PP (5 wt% PP-g-MA) Woven jute fibres

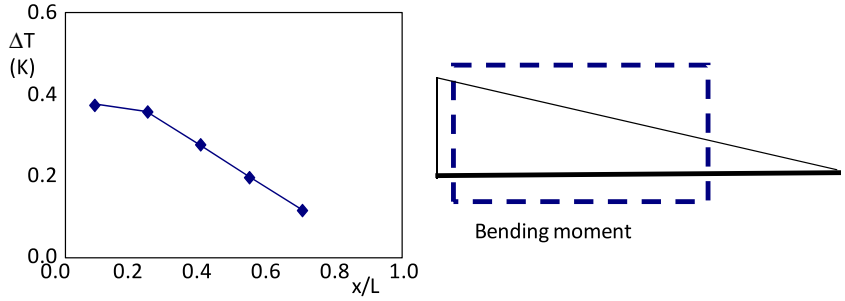

Fig. 1. Comparison between ΔT distribution and bending moment diagram for a cantilever beam.