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Fatigue assessment by energy approach during tensile and fatigue tests on PPGF35

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Abstract

Today, lightweight and low cost components can be obtained with short fibre reinforced plastics. The recyclable nature of these materials by comparison to thermoset matrixes composites is also clearly appealing.
This paper investigates static and fatigue behaviour for a glass-fibre-reinforced polypropylene composite. Tensile tests were carried out using DIC and IR Camera. Stress vs strain curves and temperature evolution associated to the applied tensile stress were determined. The trend of the surface temperature of the specimen during fatigue tests was analyzed.

Keywords: Fatigue; Thermographic Method; Digital Image Correlation; Infrared Thermography

Nomenclature

c	specific heat capacity at constant pressure [kJ/(kg K)]
f	frequency [Hz]
K_m	thermoelastic coefficient [MPa^{-1}]
N	number of cycles
N_f	number of cycles to failure
R	stress ratio
T	surface temperature [K]

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T_0	initial temperature [K]
α	thermal linear expansion coefficient [K^{-1}]
ε	strain
ρ	density [kg/m^3]
σ	stress [MPa]
ΔT	temperature increment during static test [K]
ΔT_{st}	asymptotic temperature increment during fatigue test [K]

1. Introduction

Recent advances in thermoplastic resins have improved their mechanical and thermal properties. These have made them more competitive compared to the traditional thermoset applications, especially for transport industry where they are used for panels, door frames, bearings, gears, etc. Today, lightweight and low cost components can be obtained with short fibre reinforced plastics. The recyclable nature of these materials by comparison to thermoset matrixes composites is also clearly appealing. Restricted a few years ago to automotive applications with limited mechanical requirements, these materials, filled with glass fibres up to 50% in mass, are now used for structural components as reported by Bernasconi et al. (2010), Casado et al. (2006), Sonsino and Moosbrugger (2008). The fatigue properties of polymer-matrix composites are of paramount importance for many intended applications where components are subjected to load and environmental histories which vary in time over the period of service [Reifsnider(1991)]. In particular, the fatigue behaviour of advanced continuous fibre composites have received great attention during the past 40 years as a result of the strong focus on applications in the aerospace field. Recently, efforts to reduce the weight of automobiles by the increased use of plastics and their composites, have led to a growing penetration of short-fibre-reinforced injection-moulded thermoplastics into fatigue-sensitive applications [Mandell (1991), Karger-Kocsis (1991)].

Fatigue damage is generally associated with the initiation and propagation of cracks in the matrix and/or the destruction of bonding at the polymer/matrix interface. Final failure of discontinuous-fibre-reinforced engineering thermoplastics under alternating loading mainly occurs by fatigue-crack propagation (FCP) [Hertzberg and Manson (1980)].

One of the most important applications of glass reinforced polypropylene is in automotive body panels made by low cost thermoforming techniques. The design of short fibre reinforced plastic components for structural applications requires an accurate knowledge of the several factors affecting the tensile properties and the fatigue lifetime. The tensile strength and toughness/impact energy of short fibre reinforced polymer composites would depend on a number of factors such as fibre length, interfacial adhesion and properties of components [Fu et al. (2005)].

Tensile tests were performed by Godara and Raabe (2007) using digital image correlation (DIC) for resolving the mechanical behaviour and spatial distribution of the plastic microstrains in an epoxy resin reinforced with 35 wt% short borosilicate glass fibres.

The fatigue tests of SFRP material are even more time consuming than the tests required for metallic materials because the viscous material exhibits a high heat build-up at high frequencies [Sonsino and Moosbrugger (2008)].

Pegoretti and Riccò (1999) investigated on FCP behaviour of polypropylene composites reinforced with short glass fibres as a function of fibre content and frequency of the sinusoidal applied load.

Ferreira et al. (1999) obtained and discussed the S-N curves, the rise in the temperature of the specimens during fatigue tests and the loss of stiffness of polypropylene/glass-fibre thermoplastic composites produced from a bidirectional woven cloth mixture of E glass fibres and polypropylene fibres.

Esmaeillou et al. (2011) performed tension-tension fatigue tests on SFRP composites at different applied maximum stress and analyzed the specimens at both microscopic and macroscopic scale. The temperature was measured during cyclic loading using an infrared camera and also the progressive loss of stiffness was evaluated during the tests. Moreover, the effects of the frequency and of the mean stress on the fatigue strength were evaluated.

An energy-based approach was proposed by Meneghetti and Quaresimin (2011) to analyse the fatigue strength of plain and notched specimens made of a short fibre-reinforced plastic weakened by rounded notches.

Toubal et al. (2005) used an analytical model based on cumulative damage for predicting the damage evolution in composite materials. The model is verified with experimental data from a carbon/epoxy composite fatigued under tension–tension load. Fatigue tests of specimens have been monitored with an infra-red thermography system.

Full-field measurement techniques were applied in [Steinberger et al. (2006), Goidescu et al.(2013)] for the damage investigation of composites.

The traditional methods of fatigue assessment of metallic and composite materials are extremely time consuming. In order to overcome the above-mentioned problems, an innovative approach for fatigue assessment of materials and structures has been proposed by La Rosa and Risitano (2000): the Thermographic Method (TM). The Thermographic Method, based on thermographic analyses, allows the rapid determination of the high-cycle fatigue limit. A review of the scientific results in literature, related to the application of the thermographic techniques to composite materials have been presented by Vergani et al. 2014.

A new innovation approach to determinate the fatigue limit during tensile static test has been proposed by Clienti et al. (2010) for plastic material and by Risitano and Risitano (2013) for metallic material. This approach correlated the first deviation from linearity of the temperature surface of the material during tensile test to the fatigue limit. This was observed for basalt by Colombo et al. (2012) and glass by fibre reinforced composites by Harizi et al. (2014) and Crupi et al. (2015).

This paper investigates static and fatigue behaviour for a glass-fibre-reinforced polypropylene composite (PPGF35). Tensile tests were carried out on specimens using a hydraulic testing machine and DIC and IR Camera have been used during all tests. Stress vs strain curves and temperature evolution associated to the applied tensile stress were determined. The trend of the surface temperature of the specimen during fatigue tests was analyzed.

The aim of this study is to apply the TM for the fatigue assessment of composite materials, obviously taking into account that the composites have different and more complex fatigue mechanisms respect to metallic materials.

2. Material and methods

The material used in this study is a 35 % chemically coupled high performance glass fibre reinforced polypropylene compound intended for injection moulding (PPGF35). Table 1 shows the mechanical properties of the material; the values are elaborated by a statistical study on 15 specimens. Table 2 shows the parameters should be used as guidelines for the injection moulding of the specimen.

Table 1. Mechanical properties of PPGF35.

	Tensile strength	Elastic Modulus	Failure strain	Density
	σ_R [MPa]	E [MPa]	ε_f [%]	ρ [kg/m^3]
AVG	112	8915	3,4	1216
Dev. St.	2.3	314.8	0.16	3.6

Table 2. Injection moulding parameters.

Feeding temperature	Mass temperature	Back pressure	Holding pressure	Mould temperature	Screw speed	Flow front speed
40 - 80 °C	230 - 280 °C	Low to medium	30 - 60 MPa	30 - 50 °C	Low to medium	100 - 200 mm/s

Dog bone specimens (Fig. 1) were injection moulded (type 1A of the ISO 527-2:1993 standard) with processing conditions based on ISO 294-1:1996 and ISO 1873-2:2007. The specimens were machined out from injection-moulded plates at orientation angle of 0°. Table 3 shows the dimensions of the specimen geometry; the values are elaborated by a statistical study on 15 specimens.

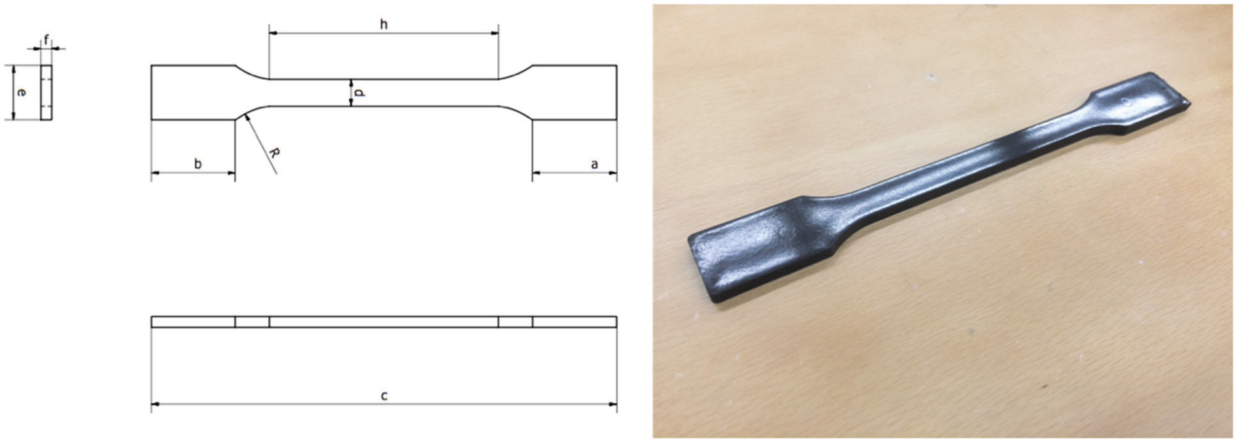
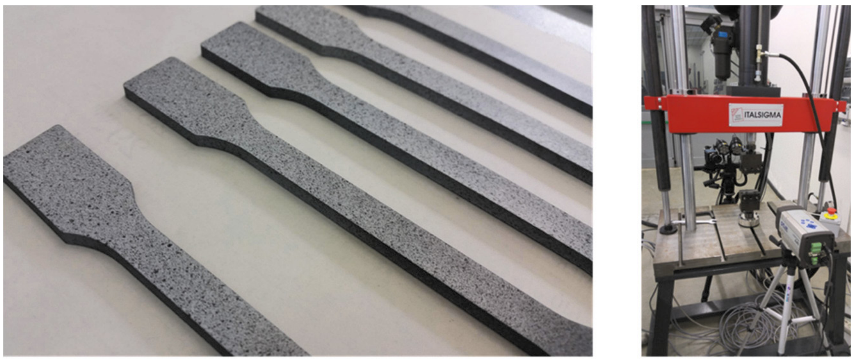


Fig. 1. Standard ISO 527-2:1993 specimen.

Table 3. Dimensions of the specimen.

	a [mm]	b [mm]	c [mm]	d [mm]	e [mm]	f [mm]	R [mm]	h [mm]
AVG	30.61	30.54	169.45	9.86	19.84	3.93	25.00	83.48
D.St.	0.18	0.13	0.37	0.02	0.06	0.01	0.00	0.26

The static tests were carried out using a servo-hydraulic load machine at a crosshead rate equal to 5 mm/min with constant relative humidity and temperature. The tensile tests were carried out on 15 specimens using a hydraulic testing machine (ITALSIGMA) and the DIC technique (ARAMIS 3D 2M LT) was used to analyze the strain pattern of the specimen surface (Fig. 2a). Two cameras with a resolution of 1600 x 1200 pixel were used. Moreover, during tensile tests, an IR camera FLIR A40 was used (Fig. 2b).



(a) (b)

Fig. 2. a. Strain pattern of the specimen surface. b. hydraulic testing machine.

The 15 specimens, investigated under fatigue loading, have the same geometry (Fig. 1) of those used for the static tests and are made from the same material by injection moulding as reported in Table 2. For fatigue tests, the following parameters were used: load ratio R= -0.1; test frequency f= 5 Hz. The tests were performed in constant stress at ambient temperature. As previously mentioned, during all the tests the surface temperature of the specimen was monitored with an IR camera. Two types of test were performed. One series of fatigue tests (11 specimens) were carried out with a constant load until failure. Other series of tests (4 specimens) were carried out with with increasing load step until failure. For three tests, four 20.000 cycles loading step from 50 MPa to 65 MPa were used. For only one test, eight 10.000 cycles loading step from 25 MPa to 65 MPa was used. The second type of test was adopted to have more points in order to determine the fatigue limit using the TM.

3. Theory and calculation

During static tests of common engineering metals, the temperature evolution on the specimen surface, detected by means of an infrared camera, is characterized by three phases: an initial approximately linear decrease due to the thermoelastic effect (phase I), then the temperature deviates from linearity until a minimum (phase II) and a very high further temperature increment until the failure (phase III). A typical trend of stress and temperature during a static tensile test is shown in Fig. 3a. For linear isotropic homogeneous material and in adiabatic condition, the variation of temperature during the phase I of the static test for uniaxial stress state is:

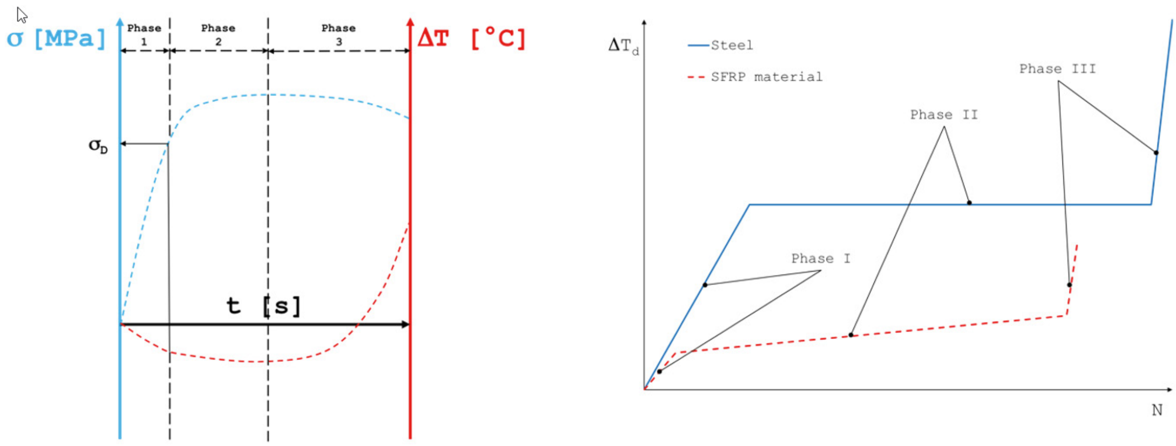
$$\Delta T_s = -\frac{\alpha}{\rho \cdot c} T_0 \cdot \sigma_1 = -K_m T_0 \cdot \sigma_1 \quad (1)$$

where K_m is the thermoelastic coefficient.

Clienti et al. (2010) for the first time correlated the first deviation from linearity, which corresponds to the end of the phase I, to the fatigue limit of plastic materials. As reported by Colombo et al. (2012) "the end of the thermoelastic phase could be related, also for composites, to a stress value σ_D, which can identify the initiation of a different kind of damage".

During HCF tests of common engineering metals, the temperature evolution on the specimen surface, detected by means of an infrared camera, is characterized by three phases when the specimen is cyclically loaded above its fatigue limit: an initial rapid increment (phase I), a plateau region (phase II), then a very high further temperature increment until the failure (phase III). The same trend was observed for metals in LCF by Crupi et al. (2011) and VHCF regimes by Crupi et al. (2015).

For that concerns the SFRP composite materials, the temperature evolution during the fatigue tests is different [Handa et al. (2011)]. After an initial linear increment (phase I), there is another linear increment with lower slope (phase II). The theoretical ΔT_d–N curves, obtained for steel and SFRP composite during constant-amplitude fatigue tests, are shown in Fig. 3b.



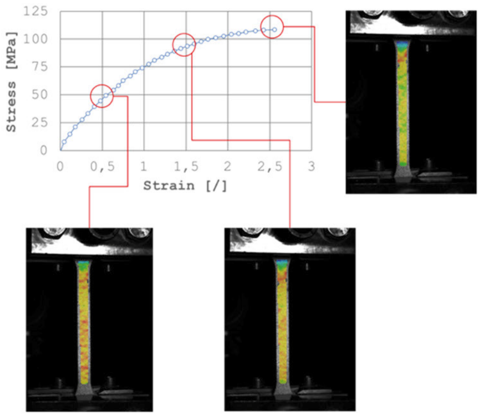
(a) (b)

Fig. 3. a. Typical trend of stress and temperature during a static tensile test. b. Typical trend of temperature during a fatigue test.

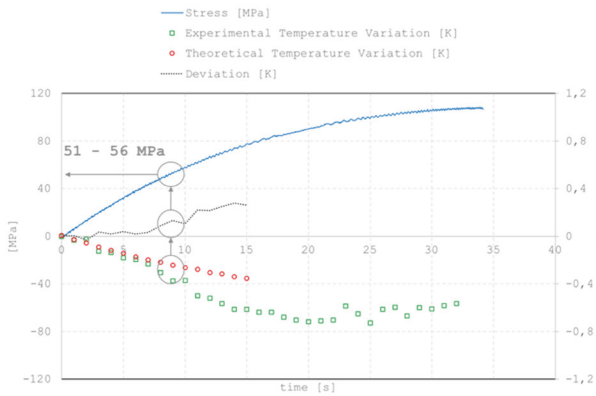
4. Results and discussions

Since the DIC technique is able to estimate the displacement field in each region of the specimen, it was applied during the tensile tests in order to obtain the stress-strain curves and to detect the failure zone at the early stages of the tests. Fig. 4a shows an application of DIC technique during a tensile test. In the figure, some images, obtained by DIC analysis during the tests, are showed along with the stress versus strain curve in order to highlight the evolution of strain in the fracture zone.

During some tensile tests, the temperature of the specimen surface was detected by means of an IR camera. Fig. 4b shows the the applied stress and the experimental temperature increment ΔT, detected by means of the themocamera, during a tensile test. In the initial part of the ΔT–t curve, an approximately linear trend is clearly visible in the curve and its slope corresponds to the thermoelastic coefficient K_m of eq. (1). In the same graph it is reported the theoretical temperature increment ΔT, obtained applying eq. (1). The values of the parameters are: density reported in Table 1; specific heat capacity at constant pressure 1.920 J/(kg·K); linear expansion coefficient $3{,}5 \cdot 10^{-5}$ 1/K. For the investigated material, the experimental ΔT has a different trend respect to the linear trend of the theoretical ΔT when the applied stress is between 51 MPa and 56 MPa as shown in Fig. 4b by deviation curve. Similar behavior can also be seen in the other tests.



(a)



(b)

Fig. 4. a. Stress vs strain curve. B. ΔT–t experimental and theoretical trend.

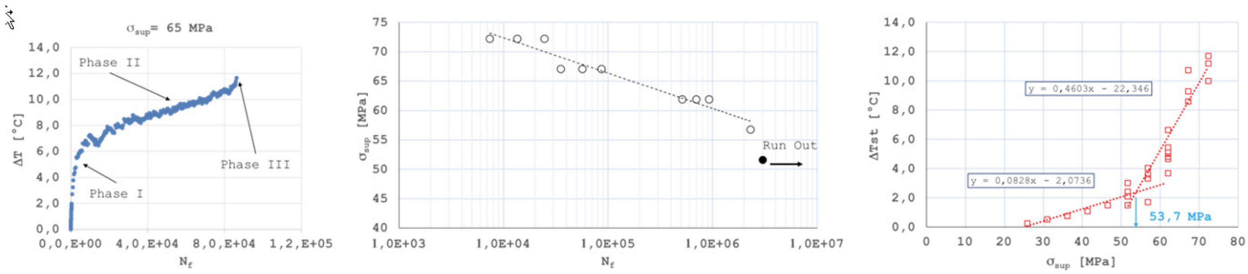
Fatigue tests at constant amplitude values of the stress range were carried out till failure at a load ratio R= 0.1. The temperature of the specimen surface was detected by an IR camera during each fatigue test. Fig. 5a plots the typical ΔT vs N curve, during a fatigue test, showing the two phases of TM, as reported by Handa et al. (2011): an initial rapid linear increment (phase I), an another linear increment with lower slope (phase II) and a sudden increase just before the specimen failure (phase III).

Fig. 5b shows the S-N data obtained applying the traditional procedure, based on fatigue tests carried out at constant amplitude of stress ranges. It is interesting to note that the fatigue strength is between 52 MPa (run out test) and 57 MPa ($3 \cdot 10^6$ cycles to failure).

Fig. 5c shows the fatigue limit predicted by the TM using the stabilization temperature applied to all the fifteen fatigue tests. It is very interesting to note that the fatigue strength is close to 54 MPa.

The values obtained using the different approaches seem to be in good agreement:

- Traditional procedure: 52-57 MPa;
- Traditional Thermographic Method: 54 MPa;
- New Thermographic Static Method: 51-56 MPa.



(a) (b) (c)

Fig. 5. a. ΔT vs N curve. b. S-N curve. c. fatigue limit predicted by the TM.

Conclusion

Full-field techniques were applied for the study of PPGF35 specimens. The DIC technique allowed the detection of strain field. The IR technique allowed the application of the Thermographic Method.

The thermographic measurements during static tests can be used to predict the fatigue limit and this procedure has been already applied to metallic materials. The aim of this study is the application of this procedure for the fatigue assessment of glass-fibre-reinforced polypropylene composite.

The predictions of the fatigue strength, obtained by means of the thermographic static method during tensile test and of thermographic method during fatigue tests, were compared with the value obtained by the traditional procedure. The predicted values are in good agreement with the experimental values of fatigue strength.

The results gave interesting information for the development of prediction models for the fatigue strengthassessments of composite material.

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