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Viscoelastic material behaviour of PBT-GF30 under thermo-mechanical cyclic loading

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Abstract

This paper deals with the simulation of the behaviour of a short glass fibre reinforced polybutylene terephthalate (PBT-GF30) under thermo-mechanical cyclic loading. Thermo-mechanical fatigue (TMF) tests, consisting of thermal cycling with a superimposed constant strain, have been carried out in the temperature ranges of -40°C to 120°C and -40°C to 40°C, applying different mean strain values. The main goal of the work is to model the stress trend during TMF cycles and assess the performance of a linear viscoelastic material model. A linear viscoelastic model has been implemented in ABAQUS 6.9-1 by means of Prony series, using the UTRS subroutine to model the time-temperature shift. The stress-time trend during TMF tests is discussed, comparing the simulated versus the experimental stress results. In particular, the maximum and minimum values within each cycle are considered, in order to evaluate the performance of the material model. Linear viscoelastic simulations show good agreement between experimental tests and FE analysis, both for plain and notched specimens.

Keywords: thermo-mechanical fatigue, viscoelastic behaviour, short fibre reinforced plastics, mechanical properties, structural simulation

1. Introduction

In the context of CO_2 emission reduction, the automotive industry makes an increasing use of plastic materials in order to take advantage of their light weight and their complex mould designs. Polymer

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matrix composites, in particular short glass fibres reinforced plastics (SGFRP) exhibit the stiffness required for some structural applications. SGFRP are widely used to build casings for electronic parts (in which metallic inserts are often included), components for on-board instrumentation, equipment and components for security systems, details of lights and countless other applications where SGFRP are used instead of light alloys or other more traditional materials. These components undergo cyclic loadings, from mechanical as well as environmental sources (temperature, humidity) during their service life. The design and study of plastic components operating under thermal cycling is extremely complex, since their properties are strongly dependent from temperature; in particular, a temperature variation induces a dramatic change in mechanical behaviour as well as in the fatigue strength of the component [1, 2]. Thermal induced stresses can originate in different ways: for example in the presence of mechanical constrains that inhibit thermal expansion/shrinkage (e.g. metallic inserts, interference fit with other components, mismatch between thermal expansion of components made of different materials, screws,…); even material anisotropy, due to fibres reinforcement can induce internal stresses. Thermal stresses add to the stress state generated by mechanical loads. The simultaneous action of mechanical loads and thermal cycling is usually called thermo-mechanical fatigue (TMF).

In the framework of a joint project between Robert Bosch GmbH and the Department of Management and Engineering-University of Padova, the thermo-mechanical behaviour of PBT-GF30 is investigated in the temperature ranges -40°C < T <120°C and -40°C<T<40°C. The main objective is the development and validation of a fatigue life assessment methodology under thermo-mechanical loading for safe design of SGFRP components. Based on Finite Element (FE) analysis of the structure, the methodology aims to estimating safely the fatigue life/strength of a component already in the design phases, reducing testing time and effort for product development. An ad-hoc testing device to carry out TMF tests on tensile specimens has been developed in order to allow for accelerated thermal cycling under strain control in combination with a superimposed constant mechanical strain (further called pre-strain). The output variable from the tests is the resulting nominal stress profile recorded at the load cell of the testing machine.

The goal of this work is to identify a suitable material model, capable of reproducing the stress profile from TMF tests by structural simulation, and to implement this model into a FE code.

A first analysis of the material models available in the current literature [2-9] highlighted that very few models already include the possibility to consider non-isothermal conditions, like the one from Dasappa *et al.* [3], at the cost of a high number of parameters required. In view of the fact that linear viscoelasticity is a common material model for the simulation of plastic materials, offering the possibility to be easily extended to non-isothermal conditions by using the time-temperature superposition principle [7], it has been chosen as material model for a first evaluation on TMF tests. For comparison purposes a linear elastic material model has been considered also. The performances of the material models have been evaluated comparing the experimental maximum and minimum stress points within each cycle with those obtained from FE simulations.

2. Thermo-mechanical fatigue testing

Thermo-mechanical fatigue tests were carried out on a MTS 858 servo-hydraulic machine, combined with a TMF testing equipment developed at the Department of Management and Engineering, in cooperation with Robert Bosch GmbH. The TMF equipment consists of couple of IR heaters, a movable cooling apparatus using a mixture of liquid nitrogen and pressurized air. Temperatures are measured by means of two thermocouples mounted in the inner and outer part of an unloaded dummy specimen positioned inside the conditioned zone near the real specimen during testing. A further thermocouple measures the liquid nitrogen expansion chamber temperature. Longitudinal strain is measured using a uniaxial extensometer mounted on the central part of the real specimen by means of springs. Extensometer gage length is 25mm. A Labview-based control system was developed for thermal cycling. Further a CCD camera with zoom lens is used to detect crack initiation during TMF tests. A technical crack length of 0.5 mm has been defined as criterion for test interruption. The TMF testing device is shown in Fig 1a.

(a) **(b)**

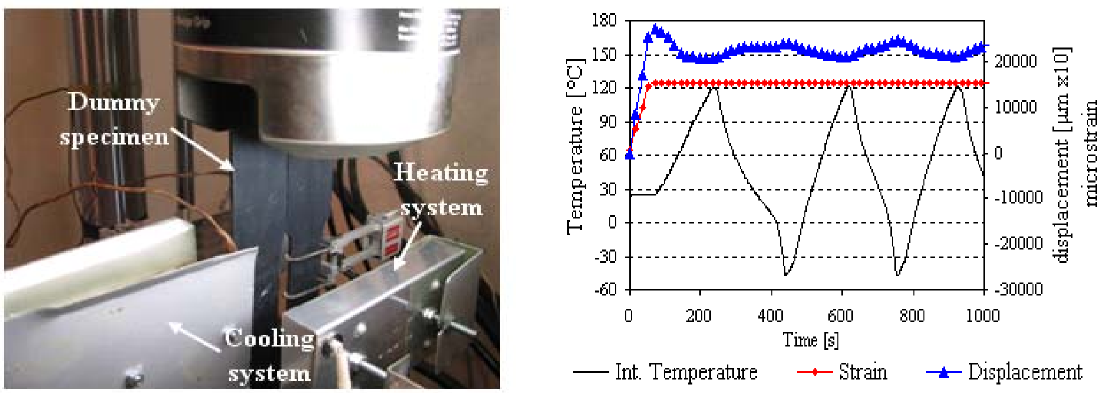

Fig. 1: (a) Experimental testing device for TMF tests; (b) Strain, displacement of the crosshead and temperature versus time.

The main steps of a TMF test can be identified as:

a) Strain ramp at room temperature (RT) until a prefixed value, further called pre-strain, with a constant strain rate of 16000 microstrain/min and then locking the strain; pre-strain values are indicated as a percent value of the tensile strain at failure measured at RT.
b) Heating-up step from RT until the maximum pre-fixed temperature value.
c) Cooling-off step until the minimum prefixed temperature value.
d) Repetition of steps b) and c) until a technical crack is detected.

A series of TMF tests were carried out on plain (net stress concentration factor k_t= 1) as well as on sharply notched (k_t = 9.8) specimens at different pre-strain levels ε_{PRE} (10, 50 and 80% of the tensile strain at failure at room temperature) in the temperature ranges -40°C < T < 40°C and -40°C < T < 120°C, as shown in

Fig. 2.

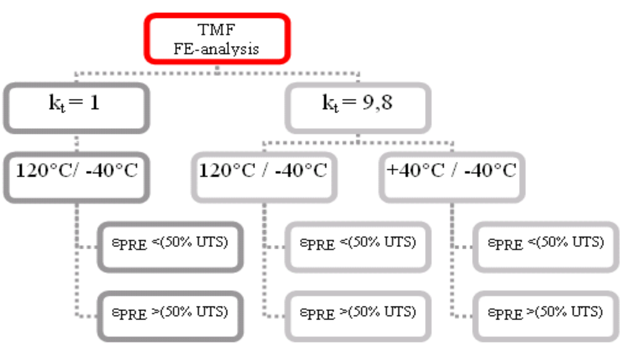

Fig. 2: Overview of TMF tests on tensile specimens considered for performance evaluation of the material model; UTS refers to the ultimate tensile strain.

During thermal cycling, only the central part of the specimen, of approximately 65 mm length, is kept at uniform temperature, with a maximum temperature gap between the inner part and outer surface of the specimen of 10 °C in the heating-up step. The tests are oriented to investigate the fatigue life under different TMF conditions. With reference to this work, the stress profile measured during the test is considered as a reference for the simulation activities, in order to validate a material model.

3. Modelling: linear elastic model

A first attempt to reproduce the stress profile during TMF tests has been carried out using an isotropic linear elastic model, coupled with a temperature dependent thermal expansion coefficient. The elastic modulus and the Poisson coefficient have been measured by tensile tests at different temperatures, while the thermal expansion of the material has been investigated in a thermo-mechanical analysis. Structural simulations have been carried out with the commercial software ABAQUS 6.9.1. The specimen has been meshed with quadratic hexaedral elements of the type C3D20R [8].

Three different approaches have been followed to carry out the FE analysis [10]. In the first approach the entire specimen has been modelled and the experimental displacement profile of the machine crosshead during the TMF test has been implemented in the structural simulation. The internal temperature values recorded during the experimental test have been applied at the entire specimen length, neglecting the temperature gradient along the specimen principal axis. In a second approach, the experimental temperature profile along the specimen length during the TMF cycle has been additionally implemented. For this purpose, the temperature profiles have been measured during the tests by a FLIR 550 infrared camera. The temperature trend has been linearized and implemented in the FE code. Finally, in a third approach, only the central part of the specimen (zone within the extensometer with an axial length equal to 25mm) has been modelled, assuming temperature within this zone homogeneous and equal to the internal, instantaneous specimen temperature measured during of the TMF cycle. In this case the displacement conditions to be used in the FE simulation are back-calculated from the extensometer signal. The last procedure allows for the best agreement between experimental and numerical strain and stress profiles and is the only one that will be further considered for discussion. Concerning the linear elastic modelling of the TMF tests with a pre-strain equal to 10% of the tensile strain at failure at RT, the numerical results show acceptable agreement with the experimental ones (Fig. 3a).

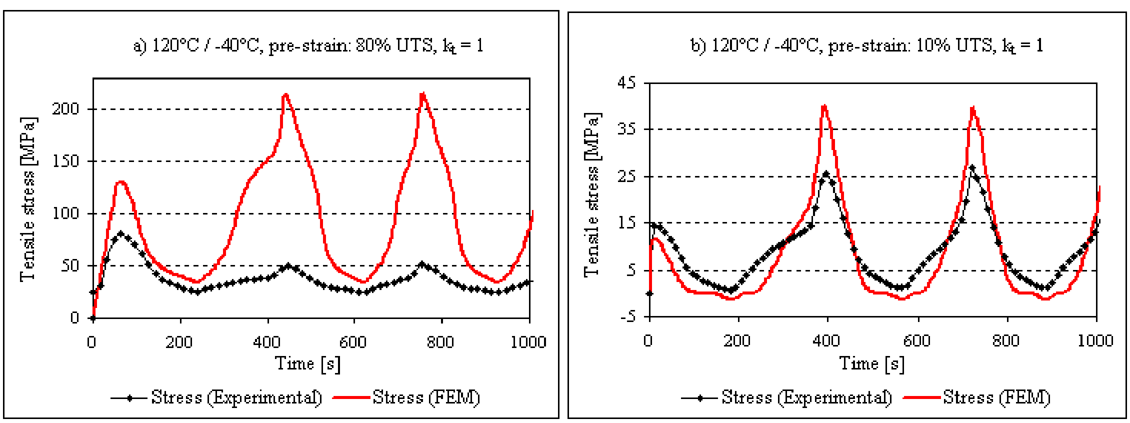

Fig. 3: Comparison between experimental results and linear elastic simulations on plain specimens in the temperature interval 40°C < T < 120°C: (a) pre-strain: 10% of strain at failure at RT; (b) pre-strain: 80% of strain at failure at RT

Considering a higher pre-strain level, however, the linear elastic model dramatically overestimates the maximal stress values (Fig. 3b). This may be associated with relaxation occurring during the test, which is not accounted for in this linear model.

4. Modelling: linear viscoelastic model

The linear viscoelastic model has been then implemented into ABAQUS code using Prony series [5, 9]. The viscoelastic material properties have been measured in a dynamic mechanical analysis (DMA) in the temperature range from -60°C to 200°C. Using the time-temperature superposition principle [7] a mastercurve has been generated with a reference temperature of 25°C. The shift factor, as a function of temperature has been defined to model the temperature dependence of the storage modulus, using the UTRS subroutine to implement it in ABAQUS. The trend of the storage modulus in the frequency domain has been fitted using a linear viscoelastic model based on Prony series [5] and further converted in the time domain; relaxation times result as fitting parameters.

The rate-independent component of viscoelastic behaviour has been defined by the instantaneous modulus, determined during the DMA test. As just done for the linear elastic model, also the linear viscoelastic model has been coupled with the thermal expansion coefficient in all simulations. The model has been validated on test with plain specimens first and with notched specimens in a further step. Considering a TMF test on plain specimens with low (10%) as well high (80%) pre-strain levels, in the temperature range -40°C < T < 120°C, the model can reasonably reproduce the stress trends (Fig. 4a). The average error in the peak stress values is about 20%. The gap could be due to viscoplastic components, arising at high pre-strain levels, which are not included in the model. The viscoelastic model has been also validated on thermo-mechanical fatigue tests on sharply notched specimens (k_t = 9.8), as displayed on Fig. 4b. Regarding to the temperature range -40°C < T < 120°C, the performance of the material model has been evaluated on two tests, with 10% and 50% of pre-strain respectively. In both cases the model can accurately reproduce the experimental stress trend. The average error on peak stress values is always lower than 15%. The largest errors occur on minimum stress levels when high pre-strains values are applied. Considering a second temperature range, namely -40°C < T < 40°C, for which relaxation phenomena occur more slowly, again a good agreement between experimental and numerical results is obtained for both pre-strain level of 10% and 50% of the strain at failure at RT (Fig. 4b).

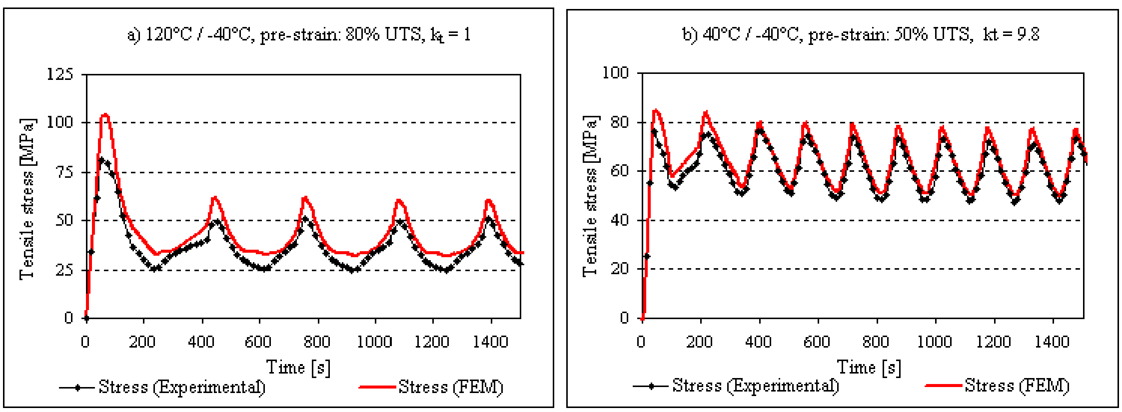

Fig. 4: Comparison between experimental results and linear viscoelastic simulations: (a) plain specimen, -40°C < T < 40°C, 80% pre-strain; (b) notched specimen, -40°C < T < 120°C, 50% pre-strain

The average error recorded on maximal stress points, which are the relevant ones for strength estimation for low pre-strain levels and is about 3%. It can be concluded that the model is suitable to reasonably reproduce the material behaviour under TMF conditions in different temperature ranges and at different strain levels with plain as well as with notched specimens.

5. Conclusions

In this paper the TMF behaviour of PBT-GF30 plain and notched specimens obtained by injection moulding is discussed. A first attempt to develop a numerical procedure to simulate the stress profile during TMF tests has been reported.

Material models from literature suitable to simulate TMF behaviour require, due to their intrinsic complexity, significant experimental efforts to estimate the model parameters; material models are usually isothermal and need be modified to include temperature-dependence.

Linear elastic simulation shows acceptable agreement with TMF tests only at low stress levels and low pre-strain values; at higher strain levels the gap between experimental and simulated stress profiles increases dramatically. The main reason of this gap is the significant stress relaxation occurring at high pre-strain levels, which is not considered by the linear model.

A linear viscoelastic model, based on Prony series and calibrated with DMA, has been further considered. The temperature dependence of the Prony parameters is implemented using a time-temperature shift factor. The viscoelastic FE simulations can accurately reproduce the stress profile during TMF tests on plain and notched specimens, in the temperature ranges -40°C < T < 120°C and -40°C < T < 40°C, for low as well as high pre-strain levels. The average gap between experimental and numerical maximum values of the stress profile slightly increases at high pre-strain levels, but is always lower than 20%. The results indicate that linear viscoelasticity is suitable to model, with a reasonable accuracy, the TMF behaviour of PBT-GF30 in all the cases investigated in the present work.

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